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ACRONYMS

°C	Degree Celsius
°F	Degree Fahrenheit
ρ	Density
%	Percentage
AASHTO	American Association of State Highway Transportation Officials
Al_2O_3	Aluminum oxide
ARA	American Retreaders' Association
ASTM	American Society for Testing and Materials
Btu	British thermal units
c	Coefficient
$CaCO_3$	Calcium carbonate
CalRecycle	California Department of Resources Recycling and Recovery
CaO	Calcium oxide
CCL	Compacted clay liner
CFR	Code of Federal Regulations
cm	Centimeter
cm/s	Centimeters per second
CM	Columbus McKinnon
CO	Carbon monoxide
CO_2	Carbon dioxide
CRREL	Cold Regions Research and Engineering Laboratory
CRMAC	Crumb rubber modified asphalt concrete
EPDM	Ethylene-propylene-diene monomer
EQUIV	Equivalent
ESPs	Electrostatic precipitators
F&B	F&B Enterprises
Fe_2O_3	Iron oxide
FIFA	Fédération Internationale de Football Association
g/m^2	Grams per square meter
GIS	Geographic Information System
GPS	Global Positioning System
H_2O	Water
HCl	Hydrochloric acid
ISC	Industrial Source Complex
ISTEA	Intermodal Surface Transportation Efficiency Act, 1990
K	Earth pressure coefficient
K_2O	Potassium oxide
Ko	Coefficient of lateral earth pressure at rest
k_h	Semi-empirical value
kcal/kg	Kilocalories per kilogram
kg	Kilogram
km	Kilometer
kPa	KiloPascals
kW	KiloWatt
kW/yr	KiloWatt per year
lbs	Pounds
lbs/hour	Pounds per hour
LCRS	Leachate Collection and Removal System
LFG	Landfill gas
m	Meter
m^2	Square meter
m^3/sec	Cubic meter per second
Mg/m^3	Macrograms per cubic meter
MgO	Magnesium oxide
mm	Millimeter

MSW	Municipal Solid Waste
MSWLF	Municipal Solid Waste Landfills
mw/yr	MegaWatt/year
NA	Not available
Na_2O	Sodium oxide
NAPA	U.S. National Asphalt Paving Association
NCAA	National Collegiate Athletic Association
ND	Not detected
NOx	Nitrogen oxide
NTDRA	U.S. National Tire Dealers and Retreaders Association
OTR	Off the Road
oz/yd^3	Ounces per cubic yard
OGFC	Open-graded friction course
P_2O_5	Phosphorus pentaoxide
PAH	Polynuclear aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PCDD	olychlorinated dibenzodioxins (dioxins)
PCDF	Polychlorinated dibenzofurans
pcf	Pounds per cubic foot
PNA	Polynuclear aromatics
psf	Pounds per square foot
psi	Pounds per square inch
PTE	Passenger tire equivalent
PVC	Polyvinyl chloride
Q	Surcharge
RCRA	Resource Conservation Recovery Act
Ref	Reference
RFP	Request for Proposals
RFQ	Request for Qualifications
RMA	U.S. Rubber Manufacturers Association
RPA	U.S. Rubber Pavements Association
RUMAC	Rubber Modified Asphalt Concrete
SBR	Styrene-butadiene rubber
SEMARNAT	Secretaría de Medio Ambiente y Recursos Naturales (Mexican Ministry of Environment and Natural Resources)
SiO_2	Silicon dioxide
SOx	Sulfur oxide
SO_3	Sulfur trioxide
STMC	U.S. Scrap Tire Management Council
TDA	Tire-derived Aggregate
TDF	Tire-derived fuel
TiO_2	Titanium dioxide
TISC	Tire Industry Safety Council
TOX	Toxicity
TRA	Tire Removal Agreement
TRIB	U.S. Tire Retread Information Bureau
TRRMMG	U.S. Tread Rubber and Repair Materials Manufacturers Group (formerly the Tread Rubber Manufacturers Group)
US	United States
USDOT	U.S. Department of Transportation
USEPA	U.S. Environmental Protection Agency
UV	Ultraviolet
WSW	White sidewall tires
YCCL	Yolo County Central Landfill

CHAPTER 1

Introduction

BACKGROUND ON U.S. – MEXICO BORDER REGION

Scrap tires pose a problem in both the United States and Mexico. In the United States alone, 275 million tires were in stockpiles in 2003, and approximately 290 million new scrap tires were generated, according to the U.S. Rubber Manufacturers Association. In Mexico, the Mexican Ministry of Environment and Natural Resources (SEMARNAT) estimates that about 40 million scrap tires are generated annually. Millions of these scrap tires are stockpiled throughout the U.S.-Mexico Border region, threatening the environmental and public health of both the U.S. and Mexico.

These piles pose a public health concern. They are breeding grounds and havens for mosquitoes and other vectors, resulting in the spread of dengue fever, yellow fever, encephalitis, West Nile virus, and malaria. Improperly managed in stockpiles, in illegal dumps, and scattered along road sides, scrap tires are a significant border environmental problem as a result of the leaching process, fires hazards, and water contamination. Once ignited, tire fires are difficult to extinguish. When water is applied to fight the fire, serious air, ground water, and surface water contamination may result. Toxic emissions from tire fires, such as sulfuric acid and gaseous nitric acid, can irritate the skin, eyes, and mucus membranes, and can affect the central nervous system, cause depression, have negative respiratory effects and, in extreme cases, cause mutations and cancer.

The scrap tire problem is heightened in the U.S – Mexico border region. There are 46 known tire piles in the U.S.–Mexico border region, according to the Border 2012: U.S.-Mexico Border Scrap Tire Inventory Summary Report (May 2007). This border region is defined by the 100-kilometer (km) area on each side of the more than 3,200–km-long (2,000 miles) border between the two countries. Throughout the entire border region, scrap tires are stockpiled at municipal solid waste landfills; junkyards; small businesses; and other privately or publicly owned properties. In 2008, the largest tire pile was located near Ciudad Juárez and it contained more than 4 million tires. Similarly, during the early stages of scrap tire management in the U.S., it was estimated that over 1 billion tires were in scrap tire piles throughout the United States. Further discussion on the tire problem can be found in the Good Neighbor 12th Report at *www.epa.gov/ocem/gneb/gneb12threport/English-GNEB-12th-Report.pdf.*

The scrap tire problem is fueled by the current economic variations within the U.S.-Mexico border region. Millions of used tires move from the United States to northern Mexican border states for reuse and disposal. Because of their lower cost, approximately half of all tire purchases in Mexican border cities are used tires from the United States. They have a shorter lifespan than new tires because they are used tires with generally 15,000 to 30,000 km (10,000 to 20,000 miles) of wear. Mexican law permits 1 million used tires to be imported across the border each year, which are reserved for the ports of entry in the states of Baja California (Tijuana and Mexicali) and Chihuahua (Ciudad Juárez). The Mexican State of Sonora also has a policy on used tire import. However, it is likely that more scrap tires may enter Mexico without proper authorization each year. For these reasons, the tire problem in the border region is significant.

Scrap tires are processed differently in the United States and Mexico. In many U.S. states, scrap tires are regulated as a municipal solid waste under the U.S. Resource Conservation and Recovery Act

Exhibit 1-1 United States – Mexico border region

(RCRA). Regulations are enforced at the state level, and most states have enacted scrap tire legislation. Common features of U.S. scrap tire programs include the following:

- Taxes on tires or automobiles for program funding
- Licensing or registration requirements for scrap tire transporters, storage, processors, and some end users
- Manifests for scrap tire shipments
- Limitations on who may handle scrap tires
- Financial assurance requirements for scrap tire handlers
- Market development.

Through these efforts, the United States has increased the number of scrap tires sent to end-use markets from 17 percent in 1990 to more than 89 percent in 2007, according to the U.S. Rubber Manufacturers Association. As of 2007, the majority of tires in the United States were processed as tire derived fuel (TDF) (54 percent), in addition to civil engineering and ground rubber applications such as landfill drainage, rubberized asphalt, filtering septic systems, and other markets.

In Mexico, scrap tires are governed under the 2004 "General Law for the Prevention and Integral Management of Waste." Under this law, every major generator of waste, including municipalities and industrial facilities, are required to develop integrated waste management plans. Scrap tires are "special management waste" under this law and, therefore, require an integrated waste management plan.

Through the U.S.-Mexico Border 2012 Program (Border 2012), SEMARNAT and the U.S. Environmental Protection Agency (USEPA) are working jointly to clean up the border's scrap tire piles and to find efficient and environmentally sound options for using them. Originating from the 1983 La Paz Agreement, Border 2012 is a results-driven partnership among U.S. and Mexican federal, state, local governments, and U.S. tribes to protect public health and improve environmental conditions along the U.S.–Mexico border. Through Border 2012, SEMARNAT and USEPA promote partnerships with industry, academia, and all levels of government as they clean up tire piles (more than 5 million scrap tires were cleaned up from 2003 to 2009) and take steps to prevent further tire piles. These steps include developing this handbook; a border-wide inventory of tire piles; a compendium of border scrap tire projects; and an ongoing multi-stakeholder group that meets annually to collaborate in finding solutions. These plus additional resources and publications can be found on the Border 2012 Waste Policy Forum website, at *www.epa.gov/usmexicoborder/fora/waste-forum/index.html*.

OVERVIEW

The Scrap Tires: Handbook on Recycling Applications and Management for the U.S. and Mexico provides a resource for federal, state, and local governments along with private industry in developing markets for the valuable resources contained in scrap tires. Specific markets and applications addressed include energy use, tire-derived aggregate, and ground rubber. Transportation and processing economics are also discussed. This handbook is intended to accelerate scrap tire market development efforts by providing critical information based on past experiences. Technical, environmental, economic, and reference information is provided for major scrap tire recycling applications to allow industry and government to assess, prioritize, target, and develop markets as efficiently and rapidly as possible. Finally, the handbook presents information and lessons learned from those who have established and effectively managed scrap tire management programs. With this information, the handbook should further efforts in preventing creation of additional scrap tire piles, thereby helping to clean up border communities. This handbook has been developed specifically for the U.S.-Mexico border although the information is useful for any country.

Whole tire erosion control wall, Los Arroyos, Mexico

CHAPTER 2

Scrap Tire Management Program Characteristics

This chapter provides information, based on the experiences of U.S. states, on setting up and implementing a regulatory tire management program. It is important to note that, although both the U.S. and Mexico have federal systems of government, historically Mexico has a more centralized, coordinated federal government, whereas powers tend to be distributed and passed down to state and local levels of government in the United States. In the U.S., although waste management is federally mandated, each state has the authority to establish the path it will follow to achieve compliance and the responsibility to manage the program. This information is based on USEPA's Scrap Tire Cleanup Guidebook: A Resource for Solid Waste Managers across the United States. Additional information on U.S. EPA state scrap tire programs can be found on USEPA's website at *www.epa.gov/epawaste/conserve/materials/tires/live.htm*. The sections in this chapter explain various aspects involved in creating and managing a scrap tire program, based on lessons learned and case studies from a number of states. These sections are:

- **U.S. State Involvement:** Describes alternative approaches that states have used to develop and fund scrap tire programs.

- **Abatement Planning:** Provides information on how states identify and map stockpiles, their quantity estimation techniques, and approaches to setting priorities among stockpiles.

- **Contractors:** Describes how states evaluate the qualifications of potential contractors (also called consultants), their bidding and award processes, the types of contracts states use, and issues regarding bonding and insurance and capacity assessment.

- **Project Management:** Based on experiences in the United States, this section discusses considerations for improving management and implementation of tire stockpile abatement or cleanup projects.

U.S. STATE INVOLVEMENT

In the United States, states are the driving force behind control and abatement of scrap tire stockpiles. Broad state adoption of regulations and regional coordination of neighboring states and local governments have dramatically decreased the incidence of illegal scrap tire storage and disposal. However, local regulations have a limited impact on controlling statewide scrap tire movement and accumulation. Scrap tires can be transported short distances inexpensively, so they usually are moved to the nearest unregulated jurisdiction or the destination with the lowest disposal cost. Concerns over the costs and hazards associated with large stockpiles as well as the proliferation of new stockpiles have driven most legislation in the United States.

Factors Influencing a Scrap Tire Abatement Program

- **Quantity:** The number of stockpiles and the total scrap tire quantity affect the abatement schedule.

- **Resources:** Financial and staff resources required to plan, contract for, and monitor multiple site abatement projects must be available.

- **Access:** Obtaining site access for abatement can be a prolonged legal process, depending on the procedures defined in the enabling legislation.

- **Infrastructure:** Capacity limitations of both contractors and markets must be recognized to avoid detrimental impacts on the use of scrap tires being generated. The overall objective should be to create a sustainable infrastructure for using scrap tire resources over the long term.

This section defines important regulatory and enforcement roles that U.S. states have assumed to control and abate scrap tire stockpiles. Many stockpiles were created decades ago, when storage was unregulated. As a result, many states are forced to fund cleanup of these "legacy" stockpiles because those involved in creating the stockpiles lack the resources necessary to clean them up. Furthermore, no single scrap tire program is universally applicable because states have different industrial, economic, political, and geographic characteristics. Therefore, this section discusses alternatives that states have successfully used in developing and funding programs.

Scrap Tire Cleanup Programs and Funding

Scrap tire stockpiles do not have a positive net value because abating stockpiles costs more than can be derived from revenue generated from scrap tire uses. If stockpile owners are unable or unwilling to fund cleanups, the stockpiles become public liabilities, and funding to abate the associated public health and environmental hazards must be provided.

States in the U.S. generally establish funding mechanisms within the legislation that initiates the scrap tire programs. In general, most programs begin by documenting the extent of the problem by identifying, quantifying, and setting priorities among stockpiles. Furthermore, the presence of a processing and market infrastructure is important because most abatement programs seek to use scrap tires removed from stockpiles.

Effective scrap tire programs generally have the following financial management characteristics:

Dedicated Funding Source

Effective scrap tire programs require consistent and continuing funding. Ongoing monitoring and enforcement programs are required to prevent new stockpiles after existing stockpiles have been remediated. Dedicated trust funds have been used successfully to achieve uniformity, but the trust fund money may be re-allocated to non-tire program priorities during state budget shortfalls. More information on fee programs and funding can be found on line at *www.epa.gov/epawaste/conserve/materials/tires/laws.htm*.

Using a Dedicated Trust Fund for Scrap Tire Abatement in Oregon

Oregon initiated its waste tire management program in 1988, depositing the net revenue from its $1.00 per tire fee (minus $0.15 per tire for the dealer and $0.035 per tire in administrative costs) in a dedicated trust fund. Between 1988 and 1993, Oregon abated 3,823,440 tires at 63 sites at a cost of $3,749,041 and undertook 101 other voluntary cleanups. The fund also supported market development and established an ongoing regulatory framework for processors and haulers. When the program ended in 1993, about $1.4 million remained in the trust fund. Enforcement efforts are now supported under the general umbrella of solid waste management fees levied on landfills.

Scrap Tire Abatement and the California Tire Recycling Management Fund

In conjunction with the California Tire Recycling Act of 1989, the state established the Tire Recycling Management Fund. Funds are collected through the California Department of Resources Recycling and Recovery (CalRecycle), previously the California Integrated Waste Management Board, program that charges $1.75 per tire on the sale of new motorized vehicle, construction equipment, or farm equipment tires. Revenues generated from the program are used for waste tire management such as research on new recycled tire use, assistance to local scrap tire program management, regulation of scrap tire facilities and tire haulers to protect public health and the environment, public education programs, storage of tires, and business development. Through this program, California estimates that approximately 75 percent of scrap tires generated in 2004 were used in some way. Since the program began, California has been able to use some of the funds generated to support several scrap tire grants, including tire cleanup and amnesty, rubberized asphalt programs, tire-derived aggregate, business assistance, and tire enforcement. These grants have been invaluable in ensuring the sustainability of scrap tire programs in the state. Additional information on California Tire Management can be found on line at *www.calrecycle.ca.gov/Tires*.

Adequate Resources

In general, funding levels equivalent to at least $1 per scrap tire have proven adequate to implement comprehensive programs, with 35 to 50 percent of the funds initially committed to stockpile abatement. Market development grants are often available to assist in launching these programs. Providing grant funding would be a viable option for programs seeking support in Mexico.

Funding Flexibility and Accrual

Abatement funds are often accrued in the early stages of the program while scrap tire stockpiles are being identified, prioritized, and legally accessed. This funding allows subsequent contractual commitments to be met and provides contingency funds for unpredictable events. As abatement is completed, it is generally appropriate to shift funding to other program priorities or to reduce revenue.

Regulatory and Permitting Programs

States have found that regulations and infrastructure are necessary for an abatement program to be effective and efficient. If management, transport, and disposal of the scrap tires generated each day are not controlled by regulations, new stockpiles will be created as old ones are cleaned up. Although some states have been successful with limited permitting or no permitting at all, others monitor tire movement with comprehensive manifest systems and require permits for all businesses involved. There have been successes and failures in both approaches. The primary objective of a regulatory or permitting program is generally to ensure the proper transportation, storage, recycling, and disposal of scrap tires and to prevent formation of illegal stockpiles.

Processing and Storage Facilities

Some of the largest scrap tire stockpiles have been created at processing facilities or at storage facilities formed in anticipation of future processing, often before state programs were implemented. Virtually all state programs regulate processing and storage locations to control scrap tire accumulation.

Storage facilities are generally required to be permitted or registered to store any scrap tire in quantities above a stated minimum that can typically range from 50 to 10,000 tires. The minimum should be carefully considered. Experience has shown the optimum quantity to be 1,500 to 2,500 tires, which allows a new tire store to accumulate a truckload of tires for optimum hauling efficiency.

Florida Enforcement Efforts Target Haulers and Tire Store Owners

As part of its efforts to control illegal dumping and formation of scrap tire stockpiles, Florida has developed regulations that require scrap tire haulers to register with the state and tire stores to use only registered haulers. Enforcement officers in one county conducted a "sting" operation when undercover officers posing as unregistered haulers offered to take scrap tires at below-market cost from tire stores. At the conclusion of the operation, 24 store managers who accepted the offer were served with warrants from the state attorney's office for a statutory violation punishable by a fine of up to $1,500 and 1 year in jail. The judge was generally lenient with the managers as first-time offenders. The sting served as a warning to store owners and focused broad public attention on proper tire disposal practices.

Processing and larger storage facilities are generally permitted or registered. Maximum storage limits are normally established during permitting. Low limits can impair efficient operations by preventing maintenance of adequate inventories to compensate for inherent variations in supply, equipment maintenance downtime, or market fluctuations. On the other hand, high limits can increase public liability.

Haulers

Haulers, or transporters, may be considered the weak link in the scrap tire management chain. The transportation part of the scrap tire business is extremely competitive, and ultimately the disposal fee represents a major percentage of the revenue that haulers collect from new tire dealers. Controls are often necessary to reduce the possibility that haulers will use inappropriate disposal measures.

One option states employ is to register haulers annually and provide decals, medallions, or placards for display at a prescribed location on each transport vehicle. This option allows enforcement officials to check compliance from their vehicles. Some states require financial assurance for each scrap tire-related vehicle or business, with varying amounts up to $20,000 per business. Small haulers are generally exempt from this measure; however, this group is most likely to illegally dump tires. Most states either do not require hauler bonds or keep them relatively small on a per-vehicle or per-business basis.

Tire Stores

Tire stores can play a key role in preventing illegal disposal of scrap tires. When a store owner or operator receives a quote for tire disposal that is below the market price, it likely involves illegal disposal. An auditable trail is maintained, however, if the owner or operator is required to keep records of the registered hauler decal numbers and the tire quantities handled. A state with a manifest system can reinforce the responsibility of stores by requiring them to maintain a copy of each completed manifest showing the ultimate disposal site, as has been done in Oklahoma and Texas. Other states require hauling and disposal receipts to be maintained on the store's property; however, the receipts are not required to be submitted to the regulatory agency. This system still allows for the regulatory agency to audit a used tire store's records without the administrative costs of a formal manifest system.

Enforcement and Cost Recovery Tactics

Enforcement and abatement cost recovery tactics are integrally linked. With a goal of facilitating site access and scrap tire stockpile removal, it is important to avoid creating legal and economic obstacles that may delay abatement. Several states allow their agencies to enter into stockpile access and abatement agreements at public expense without cost recovery. This approach expedites site cleanup, and the site owner or operator usually welcomes the assistance. However, the approach increases public expense and provides no incentive to mitigate sites. This leniency may also lead to additional stockpile formation, as the site owner may simply open another site nearby.

Illinois Use of Tire Removal Agreements

One option for avoiding obstacles to enforcement and cost recovery is use of a voluntary tire removal agreement (TRA) between the owner of a property where scrap tires are located and the regulatory agency or department. This voluntary, written agreement allows removal of all scrap tires from the property at no cost to the state. Provisions must be established in the TRA to ensure that the tire pile is cleaned up in a manner that is fully protective of human health and the environment during the entire period of the agreement. Statutory authority may allow for maximum removal schedules, such as 3 months if the site holds 1,000 or fewer tires or 1 year if the site holds more than 10,000 tires. Extensions of the removal schedule may be allowed if the property owner is operating in good faith to execute the agreement.

Forced Cleanups in Illinois

State of Illinois Compiled Statute 415, Title XIV, governs all used tire management practices; Section 55.3d of this statute enables the Illinois EPA to notify a landowner of the environmental and public health hazards associated with a scrap tire stockpile. The landowner then has an opportunity to develop, submit to the Illinois EPA, and implement an abatement plan. If the landowner is unwilling or unable to comply with the removal schedule, or does not submit a removal schedule in response to the notification, the state is granted access to the property via existing statutory authority. As an added precaution to confirm protection of the landowner's constitutional rights, the Illinois EPA uses an access agreement that is signed by the landowner before the cleanup. If the landowner refuses to sign the access agreement, the Illinois EPA will then go into court to seek site access from a judge. Illinois EPA's access agreement is available at *www.epa.gov/reg5rcra/wptdiv/solidwaste/tires/guidance/index.htm*.

Other states — Illinois, Nebraska, New York, and Ohio, for example — have provisions that allow agencies site access to conduct stockpile abatement without forfeiting cost recovery.

Dedicated Legal Assistance

Obtaining support from legal experts within a regulatory agency can be a major obstacle. Dedicating legal staff in both the regulatory agency and attorney general's office can help to achieve successful legal efforts.

Initial Legal Support

Rigorously supporting the initial legal proceedings (complaints, testimony, and depositions) with sound preparation, good research, and expert testimony can encourage defendants to take action and send a signal to others in the scrap tire industry.

Negotiations

When cases are strong and the regulatory department is determined, some site owners recognize the economic advantage of mitigating sites on their own. They can typically mobilize contractors and select disposal methods at a lower cost than the department. Additionally, they can avoid the legal costs and state administrative expenses that would be incurred in legal cases.

Judgment Collections
Only a small percentage of legal actions, or judgments, taken against site owners and operators are successfully realized. Offenders can hide assets, declare bankruptcy, or disappear. The primary value of cost recovery is to create an incentive for landowner abatement of a site, and not to realize financial judgments against offenders without assets.

Liens
Liens can be the most effective method of cost recovery from site owners. Most states do not foreclose on liens but hope to gain some revenue from negotiated interim payments or from sale of the property (especially commercial property) in the future.

ABATEMENT PLANNING

Scrap tire stockpile abatement is a technical, economic, and political challenge. Cleanups involve elusive factors such as weather, stockpile contents, and underlying topography. This section presents critical planning considerations states have used for both overall cleanup programs and individual abatement projects.

Stockpile Identification and Mapping

Stockpile identification is the first step in defining the magnitude of the scrap tire stockpile problem in any jurisdiction. The most effective methods have involved all levels of government and enforcement as well as industry groups and citizen reports.

State Government
State solid waste and public health departments play a focal role in scrap tire stockpile identification efforts and have a broad range of organizational structures. Centralized departments deploy personnel to each region of the state to work with county, city, and local officials in identifying and characterizing sites. Other departments either designate one person in each region to identify stockpiles or distribute responsibility to all staff based on geographic or industry area of expertise. Smaller identification groups are easier to train and gain greater knowledge through in-depth experience. However, these advantages can be offset by greater travel time, cost, and difficulty in making regular visits to examine changing site conditions.

One effective compromise is to use a broad base of personnel to identify stockpiles in their service areas and then task a smaller group to characterize and prioritize stockpiles. Contractors or consultants may be useful for supplementing agency resources in the early stages of program implementation.

County and Local Governments
Most effective programs have drawn on county, city, and local governments to identify stockpiles. Police, code enforcement, mosquito control, solid waste management, public health, park, firefighting, and forestry personnel have all helped to identify stockpiles they encountered during their routine activities.

One U.S. state sent surveys to all county and local governments that asked for stockpile sites to be identified by location, street address, and owner. Cooperation in these efforts can be enhanced by the survey objectives and methodology and by explaining the program’s ability to help local governments abate sites without using local resources.

Additional Identification Methods
Other creative methods can be used to support identification efforts, including the following approaches:

- A toll-free telephone number can be established to encourage residents to report stockpiles and illegal disposal.
- Both public service announcements and promotion of initial abatement activities encourage reporting of additional stockpiles.
- Representatives of tire dealers, salvage yards, and haulers can reach out within their industries to encourage stockpile identification.

Required Information
Once a stockpile is identified, characterization is conducted to gather information required for prioritization, stabilization, and abatement. The following information is particularly useful, especially for larger sites:

- Location, including street address, city, county, and global positioning system (GPS) coordinates.
- Owner or operator’s name, address, telephone number, and involvement.
- Stockpile characteristics such as dimensions, tire sizes, age, tire compaction, whether scrap tires

Border 2012: U.S.-Mexico Border Scrap Tire Inventory and Mapping

In 2007, as a step toward improving scrap tire pile management along the U.S.-Mexico border, the USEPA Office of Solid Waste (Currently the Office of Resource Conservation and Recovery) initiated a project to create a comprehensive scrap tire pile site inventory. (Scrap tire pile sites include sites where tire piles exist or have recently been cleaned up.) The primary objective was to compile existing data to create an inventory of all known tire pile sites on the Mexican side of the eastern border (along New Mexico and Texas). In 2002, USEPA Region 9 prepared a tire pile inventory for the western border (along California and Arizona) for the United States and Mexico, which was updated in 2003 and 2004. After data collected on the Mexican side of the eastern border had been compiled, these and other available data were used to create one geographic information system (GIS) map of scrap tire pile sites for the border region. This information can be found at *www.epa.gov/epawaste/conserve/materials/tires/pubs/2012-tires.pdf*.

are stacked or laced, the percentage of whole tires and shreds, and the presence of rims and other wastes.

- Site characteristics such as stockpile spacing, soil, topography, access, and drainage channels, as well as nearby surface water, residences, businesses, and population densities.
- Site conditions impacting fire control, such as access roadways, water resources, perimeter and internal fire lanes, trees, and brush.

Mapping Tip

Review of site background information, such as aerial photographs, topographic maps, or tax maps, before the scrap tire quantity is estimated can reduce the effort needed for field mapping. This information is often available in government or other Internet-accessible databases. The USEPA Scrap Tire Cleanup Guidebook also contains a section on mapping, and the information can be found at *www.epa.gov/epawaste/conserve/materials/tires/pubs/2012-tires.pdf*.

The information on site characteristics and conditions is useful for site stabilization and fire control planning for larger sites. For smaller sites, only the location, owner or operator, and stockpile characteristic information is needed.

Mapping

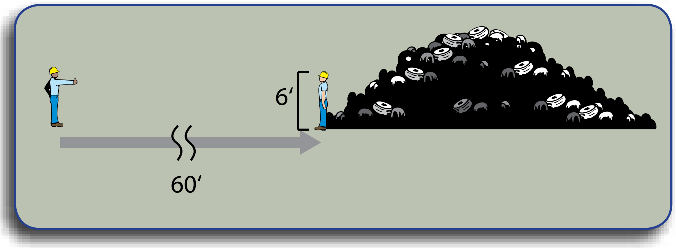
Stockpile mapping offers political, technical, and economic benefits. It allows public officials and citizens to understand the extent of the problem, as it graphically illustrates the broad distribution of scrap tire sites in the state. Mapping enhances efficiency by supporting coordination of site-related activities such as inspections.

Quantity Estimation Techniques

After stockpiles have been identified, the scrap tire quantity is estimated for prioritization, program planning, budgeting, and contract management. Stockpile estimating is relatively simple in principle, but can be affected by many variables.

During initial site identification and examination, the dimensions of each stockpile segment can be measured using one of several techniques, including a long tape, a measuring wheel, or a calibrated pace. A 100-foot fiberglass tape requires two people for efficient use and is preferable for uneven terrain or in cases likely to require court testimony. A large-diameter measuring wheel can be used on firm, level terrain but is unusable on rough or muddy ground. A calibrated pace can be used efficiently on most terrain, but its accuracy depends on the ability of the measurer to maintain a uniform pace. Taking measurements from the midpoint of the pile slope simplifies subsequent calculations. In addition, photographs should be taken during field inspections to document site conditions, to monitor changes in site conditions between inspections, and to serve as legal evidence.

Estimating stockpile depth is often a challenge because the sides are sloped and are not easily measured. One technique is to have a person of known height stand as close to the pile as possible while an observer stands back and measures the pile depth in multiples of the first person's height. The observer should be at least 10 times the estimated pile depth away to minimize angle distortion. A spotter's scope or compact measuring device can also be used. Climbing a large pile can help to collect information about top contours, pile characteristics, dimensions, and firmness (which reflects density variations associated with compaction, aging, and lacing). Tires in stockpiles are irregularly shaped, flexible, and



Determination of tire stockpile depth

unstable, so extreme care should be taken in climbing a tire pile. Stockpiles pose other risks to estimators, including disease-carrying mosquitoes, rodents, and snakes. Estimators should be alert and move cautiously.

Aerial photographs can be used to define the dimensions for a large stockpile, but a scale must be established based on nearby objects. To be effective, aerial photographs must be taken vertically to avoid dimensional distortion. Depth and density estimation requires ground observation. Detailed aerial surveys can be conducted, but the ground topography under the pile must be known or assumed. Aerial surveys are expensive, and their accuracy is questionable unless a pile is deep enough to reduce the margin of error associated with irregularities in surface depth.

As a first step, the stockpile volume is estimated using calculations based on the dimensions. In some cases, irregular shapes in the tire pile can be converted into rectangles, circles, or other simple geometric shapes to simplify calculations without impairing accuracy. In other cases, a single irregularly shaped pile can be measured as two or more connected rectangular segments with different dimensions. If dimensions have been measured from the midpoint of the slope, the volume of a rectangular pile is simply the total of multiplying the length, width, and depth. Although this method is not geometrically perfect, the simplification does not significantly alter the total volume estimate.

The second step in estimating the tire quantity in a stockpile is estimating the pile density, or the quantity of scrap tires contained in each cubic meter, or yard, of the pile. Volume is translated into quantity or weight through assignment of a density. Because most tire stockpiles contain mixtures of various tire sizes, density is normally expressed in terms of the passenger tire equivalent (PTE), which is equal to 9 kg (20 pounds) by definition. The densities of most scrap tires are roughly equivalent when expressed in

The volume of common stockpile shapes can be calculated with the following formulas:

Circle

$\Pi r^{2} d$ = 3.14 x circle radius x circle radius x depth

Triangle

½ lwd = ½ x length x width at base x depth (from base to peak of pile)

Trapezoid

½ l (w1 + w2) d = ½ length x (width at base + width at top) x depth

Determination of tire stockpile volume

Table 2-1. Pile Quantity Estimation: Whole vs. Shredded Factors Affecting Tire Density

Whole Tire Stockpile	Shredded Tire Stockpile
Depth: Increases the compaction of tires in a pile and therefore increases density. **Age:** Allows additional compaction over time and therefore increases density. **Heat:** Increases the flexibility of tire rubber, thereby increasing compaction and density.	**Shred size:** Smaller shred size generally increases density. **Wire content:** Wire removal decreases density. **Depth:** Depth increases compaction and density caused by overlying tire shreds (pieces). **Equipment movement:** Equipment movement on ramps or top surfaces during stacking significantly increases density as well as probability that the pile will spontaneously ignite.

terms of PTE/cubic yard. For instance, a medium truck tire weighs approximately 45 kg (100 pounds or five PTE) and occupies a volume equivalent to four to five passenger tires in a given stockpile. The equivalency more accurately reflects future tire use, processing, and disposal because most abatement activities and other considerations are based on weight.

The density of loose, shallow, whole-tire stockpiles is normally about 10 PTE/cubic yard but can range from 8 to 27 PTE/cubic yard. Densities below 10 PTE/cubic yard reflect rimmed tires that do not collapse but account for only the rubber weight under the assumption that rims will be removed before tires are transported. Stacking or lacing increases the effective density to 12 to 15 PTE/cubic yard for passenger tires and to 13 to 18 PTE/cubic yard for medium truck tires.

The density of shredded-tire stockpiles can range from 30 to 90 PTE/cubic yard (600 to 1,800 pounds/cubic yard). The lower density range represents shallow, un-compacted piles of uniformly large particles such as single-pass shreds. The higher range represents deep stockpiles of finer tire-derived fuel (TDF) that has been heavily compacted by repeated movement of heavy equipment during stacking. The highest range represents a mixture of compacted tire shreds and dirt.

Once the stockpile volume and density have been estimated, the tire quantity (or weight) is calculated by multiplying the volume (cubic yards) by the density (PTE/cubic yard). The result is a tire quantity expressed as PTE. The tire quantity can also be expressed as a weight (tons) by dividing by 100 PTE/ton.

Although the estimating methodology described above has been successfully applied to hundreds of scrap tire stockpiles, the following factors may affect its accuracy:

- **Topography:** The underlying topography can significantly affect pile volume and tire quantity, but may not be apparent from surface observations. Larger tire piles are more difficult to estimate because they may conceal ravines or pits filled with tires. Piles located on hillsides are also difficult to estimate because hillsides may curve or become steeper beneath the piles.
- **Non-uniformity:** A pile may appear to consist of loose tires on the surface, but laced tires or shreds may be present in the pile, significantly increasing pile density and tire quantity.
- **Contamination:** Piles can be contaminated with water, soil, automobile parts, or other waste that may not be visible from the surface. Water and dirt can significantly increase pile density and abatement costs.

Stockpile Prioritization

With the understanding that resources are limited, stockpile stabilization, abatement, or both, should be initiated following a prioritized sequence based on the comparative hazards posed by various sites. A prioritization system may reflect impacts on citizens and the environment, and particularly impacts on sensitive receptors such as schools, hospitals, daycare centers, and nursing homes.

One prioritization method uses stockpile size as a multiplier because it typically magnifies the impacts of a tire fire. The multiplier ranges should reflect the quantities of tires in the piles being prioritized. For example:

Less than 100,000 tires = 1
100,000 to 250,000 tires = 2
250,000 to 1,000,000 tires = 3
More than 1,000,000 tires = 4

Table 2-2. Factors to Consider When Evaluating Impacts of Scrap Tire Stockpiles

IMPACT	AIR	WATER	POPULATION
ISSUE	Impact of fire plume on residents, businesses, and regional air quality	Impact of the contaminants found in tire rubber and residual ash on surface water or groundwater	Impact of existing stockpile on area residents
FACTORS TO CONSIDER	• Prevailing wind direction • Stockpile characteristics such as height, trees and brush, and fire lanes • Surrounding land use • Sensitive receptors such as schools, airports, and large public facilities (within 0.5- and 5.0-mile perimeter)	• Soil characteristics such as permeability • Aquifer characteristics such as water table depth and drinking water use • Site drainage • Surface water proximity • Sensitive receptors such as wetlands, fisheries, or endangered species • Stockpile characteristics	• Population proximity • Mosquito species • Identified local/regional mosquito-borne diseases • Rodent/snake infestation • Stockpile characteristics

The potential impact on the general categories of air, water, and population are often evaluated independently (based on data from the initial site evaluation) using a scale of 1 to 10, with 10 indicating the greatest potential impact. These three ratings are added and multiplied by the size factor. Stockpile size is an important consideration, but impact is the controlling issue.

Stockpile sites can then be prioritized based on the resulting rating totals, with the highest rating representing the highest priority. Sites generally fall into rating groups with numerical separations between the groups. Within groups, rating differences are generally small, and the abatement sequence can be based on site access, contractor availability, markets, or location.

Consistency is an extremely important component of any stockpile prioritization system, so using the smallest possible number of evaluators will increase consistency. However, it can be beneficial for two or three evaluators to compare their ratings so that subjective inconsistencies can be identified and corrected.

Some states use independent contractors or consultants to manage or perform stockpile prioritization to limit political influences. Using a technically sound prioritization process conducted by unbiased evaluators also improves program development.

Property Issues

Scrap tire stockpiles are generally located on property that is owned and controlled by one or more individuals. Before a scrap tire remediation project begins, it is essential to obtain either a written property access agreement from the landowner or a court order granting property access for tire removal. At many sites, a property boundary survey is also necessary to ensure that remediation work does not inadvertently extend onto adjacent properties. If additional properties are involved, additional property access agreements or court orders will be needed.

The following issues should be considered in dealing with properties:

- **Utilization:** A property can contain buildings, other structures, and public utilities, such as electricity, natural gas, water, and/or sewage, which could be useful to a contractor during on-site activities. If any of these items are to be used, a written agreement establishing use conditions, obligations, and compensation can prevent subsequent misunderstandings.
- **Damage:** States have been sued for damage done by contractors acting as their agents. In some cases, the damage has been done by others before cleanup began. As a preventive measure, complete and dated sets of photographs before, during, and after site abatement are useful for documenting site conditions.

- **Restoration:** Water in tires and rain create muddy conditions in unstable soil under a stockpile. Heavy equipment can create deep ruts, and water runoff can erode surface soil. After tires have been retrieved, contractors are generally required to level heavily rutted land. In most cases, re-establishing vegetation will control erosion.

Recognizing a property's value while obtaining and maintaining the landowner's cooperation facilitates abatement operations. If the property owner will not cooperate, a court order must be obtained to enter the property and remove the scrap tires. State legislation can aid this process if laws are enacted to create an administrative process for ordering scrap tire cleanups. One example is Ohio Revised Code 3734.85, which can be found at *www.ohio.gov/government.htm*.

Communications

Stockpile abatement involves many groups, including contractors, local governments, politicians, and the press. Informing and coordinating these groups are critical to successful scrap tire programs and abatement projects.

Contractors

Any special abatement project requirements should be clearly defined in detailed plans and specifications provided to prospective contractors in advance of the bidding process. Examples of items that should be addressed in such plans are as follows:

- Site description
- Tire quantity estimate
- Tire pile length, width, and height
- Operating procedures
- Fencing
- Lighting
- Security
- Fire lanes
- Pile removal sequence
- Stabilized access and perimeter roadways
- Control of vegetation, mosquitoes, and run-off
- Water source and distribution
- Fire plan
- Utilities
- Progress reporting

Many contractors have developed their own abatement methods to optimize the efficiency of cleanup operations based on years of experience. An initial description of the project should be developed to provide a sound foundation for project communications and to minimize the need for extraneous discussion of activities planned. Example pre-bid documents prepared by the States of Iowa and Illinois are available at *www.epa.gov/reg5rcra/wptdiv/solidwaste/tires/guidance/index.htm*.

Elected Officials

Local and state elected officials are instrumental in creating and maintaining abatement programs. Providing updates on program implementation and abatement projects is important. Inviting elected officials to view stockpile sites before and after cleanup creates a good public relations opportunity.

Local Governments

Local administrators and police and fire departments can provide critical support services at little or no cost if they are included in project communications. Informing these groups about project plans and associated benefits to the community enhances cooperation.

Partnerships

Inter- and intra-governmental department taskforces, public-private collaborations, and multinational partnerships are able to accomplish a great deal as they can encompass the entire area, pool assets and resources, and work together to create and carry out abatement programs. Enhancing cooperation and building relationships on both sides is an added benefit to these partnerships. Information on U.S. and Mexico scrap tire partnerships can be found at *www.epa.gov/Border2012/fora/waste-forum/tires-done.html* and in the 12th report of the Good Neighbor Environmental Board at *www.epa.gov/ocem/gneb/gneb12threport/English-GNEB-12th-Report.pdf*.

Press

Publicity allows citizens to understand an abatement program and the value received for public fees. In addition, publicity allows politicians and program participants to be recognized for accomplishing removal objectives. However, drawing attention to stockpile abatement projects before the cleanup is finished can have undesired effects. For example, many fires are actually started by site operators or local residents in the wake of publicity over cleanup. One approach is to issue a press release highlighting the last scrap tire being thrown onto a truck by a local community leader; the release can include site photographs taken before and during abatement.

Tire Initiative Collaborative Effort

Border states, municipalities, and the tire industry are working together to address the border's tire problem through a Border 2012 initiative called the Tire Initiative Collaborative Effort. The purpose of the collaborative effort is to increase awareness and understanding of the U.S.-Mexico Scrap Tire Integrated Management Initiative, a scrap tire management framework.

Partners

Environmental Secretariats: On August 14, 2008, the heads of the environmental departments in all 10 Border States formally signed a Tire Initiative Letter of Understanding at the Border Governors Conference in Hollywood, California. The 10 Border States include California, Arizona, New Mexico, Texas, Baja California, Sonora, Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas.

Border Governors: At the XXVI Annual Border Governors Conference, a joint declaration was signed by border state governors to execute the tire initiative among the Environment Worktable representatives.

Border Municipalities: AA number of border municipalities have agreed to take steps to implement the Tire Initiative.

Border Legislative Conference: At the 16th Border Legislative Conference on October 19, 2007, state legislators from the U.S. and Mexico expressed their support for the tire initiative.

Tire Industry: The U.S. and Mexican tire industries, represented by the U.S. Rubber Manufacturers Association (RMA) and the Mexican Chamber of Rubber, are committed to collaborating with the U.S. and Mexican governments to solve the tire problems on the US-Mexico border. RMA signed a letter of understanding on May 18, 2008.

For a more detailed listing of current partnerships between the U.S. and Mexico visit *www.epa.gov/usmexicoborder/infrastructure/index.html*.

U.S.-Mexico Scrap Tire Integrated Management Initiative

USEPA and SEMARNAT agree that implementation of the U.S.-Mexico Scrap Tire Integrated Management Initiative principles and actions are necessary for proper management of scrap tires in the U.S.-Mexico border region. The tire initiative was accepted by the Border 2012 Tire Group and signed by SEMARNAT and USEPA in October 2006.

Tire Initiative Principles

Better understand the problems contributing to scrap tire generation

Prevent new tire piles

Clean up "legacy" (existing) tire piles by environmental sound and cost-effective solutions

Involve stakeholders and communities in creating solutions

Tire Initiative Actions

Gather information to better understand scrap tire generation.

Encourage development and implementation, through incentives, of environmentally acceptable and economically viable end-use markets for scrap tires to increase recycling and reuse.

Abate tire piles by seeking funding to eliminate existing scrap tire piles, and by investing in temporary storage/transfer stations to facilitate tire recycling and reuse.

Involve federal, state and local government, business, universities, and nongovernmental organizations in the implementation of the Scrap Tire Integrated Management Initiative.

Support educational outreach programs on scrap tire recycling and reuse targeting diverse groups of stakeholders.

CONTRACTORS

The success of a scrap tire abatement program hinges on selecting contractors capable of carrying out the required tasks cost effectively in accordance with procedures and schedules. In many early abatement efforts, scrap tire processors were developing field operating experience, equipment was evolving, maintenance requirements were being defined, limited capital prevented use of efficient tire retrieval equipment, and few product markets existed, leading to project delays and failures. Although abatement still poses substantial challenges, the cumulative benefit of past experience, equipment improvements, appropriate retrieval equipment, and substantial market development has greatly enhanced the probability of success. One key to success is selection of contractors with good performance records and the ability to perform at a reasonable cost. This section defines critical factors and alternatives for successful evaluation and selection of stockpile abatement contractors.

Evaluating Contractor Qualifications

The amount of information requested from contractors during the evaluation process varies widely. Some state agencies request comprehensive data, while others simply request contact and pricing information. Below are the primary factors that have been used to evaluate contractors:

Company History

Some contractors and processors have changed their names frequently, especially after failed projects. Requiring a contractor to identify all of its previous names and affiliated companies and to provide organizational charts can help the agency understand the contractor's history.

Company Financial Capabilities

Financial strength increases the probability that a contractor will have appropriate equipment and will be able to overcome unexpected problems. To identify the financial strength of contractors, some states request 2 or 3 years of financial data. Some privately held companies are reluctant to provide these data unless confidentiality can be maintained. An alternative is to require a contractor to document its ability to provide a bond or other financial assurance for an amount equal to the maximum required for the proposed abatement activities. This approach protects the agency's financial interests and avoids confidentiality concerns.

Experience

Positive project experience increases the probability of future success, so it is critical for a contractor to document its experience on comparable projects. A contractor should describe its previous work in detail and should submit customer contact information to allow the agency to verify performance claims.

Equipment

Stockpile abatement involves tire retrieval, transport, and processing. Requiring a contractor to list and describe the major equipment to be used facilitates the evaluation. Retrieval equipment generally includes an excavator for larger sites, a front-end loader with a specially equipped bucket system for medium-sized sites, and a tracked bobcat with an appropriate bucket for smaller sites.

Transport equipment typically consists of standard 18-wheel trucks and trailers. High-volume trailers enhance efficiency if long-distance transport of whole tires is required. Some contractors use subcontractors to haul tires; information on the subcontractors, such as their licensing or relevant qualifications, should be required during the bidding process.

Tires can be processed on site or at a centralized processing facility. Processing equipment requirements depend on product and market specifications. A smaller product size specification normally requires multiple-size reduction units in series or extensive re-processing within a single unit (with a proportional decrease in effective capacity). The impact of dirt, rocks, and other contamination is generally proportional to the processing requirements. Large tire chips for highway embankment applications require less processing, but soil contamination must be removed. Nominal 1-inch-diameter TDF has been produced at stockpile

Improperly discarded tires
Photo courtesy of Brian Wright, Georgia

sites, but dirt contamination significantly increases equipment maintenance requirements and associated downtime. It is generally not possible to produce crumb rubber from stockpiled tires unless they are unusually clean and are carefully retrieved.

Products and Markets
A contractor should be required to identify the intended uses for processed scrap tires and what percentage of the products is expected to be from stockpiled tires. In general, this percentage should not exceed 15 to 25 percent of the current-generation tires. In addition, the contractor should identify product specifications and an existing contractual basis with a customer who wants the processed scrap tire product. Lack of a contractual basis increases market vulnerability and the probability that products made from current-generation tires will be displaced. The proposed processing equipment must be capable of generating products that meet the specifications.

Wastes
In some cases, contractors have received premium payments associated with scrap tire recycling while actually recovering only a very small percentage of tires as usable product. Substantial volumes of tires have been discarded or landfilled without the prior knowledge of the contracting governmental department. For this reason, a contractor should identify projected waste volumes and disposal methods so that the contracting governmental department can consider recovery percentages in its evaluation. On the other hand, the contracting department should not preclude landfill disposal of heavily contaminated tires or shreds.

Personnel
A contractor should identify specific management personnel and their prior experience, including the on-site personnel who will be responsible for daily operations and equipment maintenance.

Availability
Many contractors have limited equipment and may be involved with multiple sites prior to a new contract award. For this reason, a contractor should identify its anticipated mobilization time requirement and proposed start date; alternatively, an early start date can be established to reveal whether a contractor can perform according to the schedule.

Cost
The contracting department can require a contractor to submit a bid based on a fixed price for the total site abatement. In general, contractors build a substantial safety factor into fixed-price bids, increasing the cost per ton of material to be removed. Most current abatement activities are performed on a cost per ton basis to enhance cost effectiveness. The risk associated with this approach involves additional costs associated with contamination, such as soil or automotive parts. To control abuse, retrieval and loading operations should be closely monitored, and the contracting department should reserve the right to adjust weights to control excess contamination.

Bidding and Award Process

States have used a wide range of approaches in the contractor bidding and award process. One major variable has been the amount of information requested in request for proposal (RFP) documents. In some cases, only a fixed price was requested, and the project was awarded solely on this basis. One state used this approach during initial site abatement activities, and the contractors selected were inexperienced, underfinanced, and offered low bids based on a misunderstanding of the abatement requirements.

An alternative RFP approach for major stockpile sites is to require contractors to provide detailed responses to the criteria cited in the previous subsection to increase the factual basis for evaluation. Less information may be requested for smaller sites or when the contracting department already has a thorough understanding of a contractor's capabilities based on previous experience. Each criterion included in the RFP should be weighted based on their importance. A minimum of three experienced staff should evaluate and score proposals, with the total scores controlling contractor selection.

Conducting a detailed RFP process for each site can be cumbersome and time-consuming for all parties, especially if multiple sites are to be abated. An alternative is to pre-qualify potential contractors through a modified RFP or a request for qualifications (RFQ) process. Florida has used a pre-qualification process successfully since 1989. The process is repeated every 3 to 4 years to allow for changes in industry participants. Illinois relies on a similar pre-qualification process so that contractor responses include binding cost data presented on a price per ton basis. When a site is identified for abatement, a contractor is selected based on the site's proximity to the contractor's processing facility. The lack of individual site bidding does not result in significantly higher abatement costs.

Contracts

The form of an abatement contract depends on the bidding and award procedures used as well as state contracting requirements. There are two main categories of contracts:

- Individual site contracts created solely to cover specified abatement activities associated with an individual or conjoined stockpile. These contracts are typically awarded based on single-site RFP responses.
- Task assignment contracts created to cover general conditions associated with stockpile abatement at more than one site. These contracts are supplemented by task assignment documents covering specific site conditions as awards are made.

Each state has its own contracting procedures and contract requirements, so it is not possible to provide a "model" contract. However, examples of basic contract documents are available at *www.epa.gov/reg5rcra/wptdiv/solidwaste/tires/guidance/index.htm*.

Bonding and Insurance

The primary purpose of bonding and insurance requirements is to protect the contracting government agency from financial loss as a result of contractor error or failure to perform. A secondary purpose is to ensure that a contractor has adequate resources and is committed to successful project completion.

Historically, contracting agencies have required bonding or other financial assurance equivalent to 50 to 100 percent of a project's estimated cost. In addition, a bond typically remains in force until the contracting agency confirms final project completion and releases the bond. When bonds were relatively easy and inexpensive to obtain, the bonding requirement was not normally a hardship, except for companies with poor operating statements or balance sheets.

Recently, however, it has become more difficult and expensive for smaller companies (including many successful contractors) to obtain bonds. Some companies have resorted to alternative methods such as letters of credit or cash deposits. In some cases, large financial assurance requirements can be burdensome for contractors, as they tie up working capital resources needed to execute contracts. In other cases, these requirements may exclude experienced contractors from competing. Iowa and Virginia have no financial assurance requirements and have not experienced any contractor failures, but these states have a long history of successful contractor performance.

Capacity Assessment

The tire processing industry and product markets have a finite capacity to process and use current-generation tires and tires from stockpile abatement. Abatement objectives should consider the context of local and regional capacity to avoid disrupting the market. For instance, if the capacity of local or regional processors is limited, they can be made aware of anticipated tire volumes and may choose to increase their capacity. If not, mobile processors can be solicited from a broader geographic area. If markets are limited, others can be created through government cooperation or incentives. For example, New York considers use of tire chips from stockpile abatement for embankment projects if the chips have a lower delivered cost than other aggregate alternatives. If economic imbalances are not correctable, program objectives should be adjusted to reflect realistic tire volumes or to allow tire disposal to avoid market disruption.

On a smaller scale, assessing a contractor's processing and marketing capability to absorb stockpiled tires without disrupting use of currently generated tires can be a reality check on contractor projections. Identification of processing capacity should be based on the historically demonstrated performance of similar processing equipment, and not on equipment supplier claims.

PROJECT MANAGEMENT

The preceding sections provide the foundation and considerations for establishing a successful scrap tire abatement program based on the experiences of U.S. states. However, once abatement projects are under way, new issues arise. This section discusses factors that will enhance project management and implementation.

Site Survey

Before site mobilization, the property boundaries should be reviewed or surveyed to verify that all tires and planned access routes are located on the property. Often, tire piles extend across property lines. In these cases, written property access agreements with neighboring property owners will be needed.

Equipment

Proper equipment selection depends on site conditions, and unique site conditions may require specialized equipment or safety procedures. For instance, a tracked excavator is an efficient, high-volume tire retrieval tool if the following conditions exist:

- Open-top trailers can be moved adjacent to the stockpile for direct loading, minimizing excavator movement.
- Boom (arm and bucket of excavator) movement is not impaired by large trees or other obstacles such as power lines.
- The stockpile is deep, but the top is reachable.
- Contaminating metal objects are large enough to be seen and separated prior to loading.
- The bucket is closed above ground level to minimize soil entrapment.

In some cases, smaller equipment such as a loader or tracked bobcat can be more efficient and inexpensive than an excavator. For instance, an excavator loses many of its advantages if tires are simply being staged for loading into enclosed trailers. A skid loader can easily place tires in the end of a trailer. In addition, changing site conditions can alter equipment needs during a project. Contractors need the flexibility to make adjustments, provided that the schedule and safety are not compromised and no increased contamination or site damage results.

Transportation

Registration and Permitting – Many states require processor and hauler registration. All necessary registrations and permits should be obtained ahead of time to avoid unnecessary delays.

Weighing – Load weight can change during transport. Trapped water can drain during tire movement, or rain can add weight if water is trapped in exposed tire casings. In other cases, tires may be added to trailers in transit. If possible, trailers should be weighed at a pre-approved scale near the abatement site and again at the receiving site. The lower of the two weights should be used for invoicing.

Tire Rims – Rims can double the transport weight of passenger tires. Removing rims prior to transport will reduce transport and processing charges based on weight. If rim removal is not feasible, a tracking and weight adjustment method should be established, especially for sites such as salvage yards that have high percentages of rimmed tires. When tires are de-rimmed, both the scrap metal rims and the tire-balancing lead weights removed provide a source of revenue. The contract terms should clearly state whether the contractor retains this revenue, shares the revenue with the government department, or submits all the revenue to the department.

Rail Transport – Transportation of shredded tires in bottom-dump railcars can be problematic if chips compact and rainwater freezes. The chips then become difficult to dump at the receiving site. Side-dump and arm-dump railcars generally do not encounter this problem.

Monitoring Logs – Up-to-date records of scale tare (empty container) weights and loaded weights must be kept for all vehicles. Unit numbers must be noted on weigh slips to avoid discrepancies that can delay invoice payments.

Environmental Factors

Water

Water can create serious problems at a stockpile site. Storm water can accumulate in low spots, impeding equipment movement and operating efficiency. Also stockpiled tires spill trapped water during retrieval and handling, creating unstable soil at the site. These problems can be resolved by creating drainage channels or constructing elevated paths for equipment. An alternative is to rotate work areas to allow wet, unstable areas to dry. As unstable ground is exposed under piles, silty runoff can drain from the property to adjacent streams, ponds, and properties. Silt fences can prevent this type of runoff from the project site.

Roadways

Heavy truck movement can destroy dirt roadways at sites during wet or thaw periods. If used by area residents, the road surface must be kept passable for normal vehicles.

Dust

During dry conditions, equipment movement on unstable soil and roadways can generate dust plumes. If airborne dust affects abatement operations, on-site personnel, or adjacent properties, water can be sprayed for dust control.

Noise

Tractor-trailers, heavy tire-retrieval equipment, and on-site shredders are noisy. In populated areas, abatement operations can be limited to daylight hours to control noise impacts on nearby residents.

Security

The primary objectives of site security are to prevent the addition of tires to a site, prevent fires, and protect equipment. The security measures discussed below have been effective in accomplishing these objectives.

Vehicle Access Control

The most common approach for vehicle access control is a locked chain extending between secure posts. The chain can be removed for inspection or abatement, and most emergency response vehicles carry lock cutters in the event that they require access to a secured location.

Fencing

Preventing all vehicle and pedestrian access to a site is difficult, but casual access can be controlled by fencing. Chain-link fencing and gates may already be present at industrial sites. A rural site may have multiple entrance points, so the entire perimeter should be checked for signs of unauthorized activity.

Lighting

Lighting increases the probability that intruders will be observed but is effective only when combined with security guards.

Security Guards

Security guards can control site access and provide an early warning in the event that a fire occurs. To be effective, guards must have adequate lighting and must patrol the site in spite of mosquitoes and adverse weather conditions.

Additional Measures

Guard dogs can deter intruders at fenced sites, but dogs raise liability issues and can be injured by loose wire at processing sites. Motion detectors have been considered for sites, but animal movement in rural areas triggers false alarms. Cameras have been used at sites but generally fail to provide adequate picture quality to support capture or arrest of an intruder. Smoke detectors and heat sensors have been considered for fire detection, but the associated expenses and logistics are problematic for abatement sites.

Fire Planning and Prevention

The greatest risk associated with scrap tire stockpiles is their possible ignition. Once ignited, stockpile fires tend to spread rapidly, generating massive quantities of smoke, oil, and contaminated soil and water that cause environmental damage. Factors associated with stockpile fire planning and prevention are discussed below.

Owner or Operator Role

Many stockpile fires involving arson start during enforcement proceedings to require cleanup or initial abatement activities. This indicates that the landowner may be seeking revenge or attempting to avoid paying for his share of abatement costs. As a general rule, it is five to 10 times more expensive to remediate a scrap tire site contaminated by a fire than to simply remove the tires.

Emergency Response Plan

An emergency response plan should be developed for a large stockpile site to support coordinated notification and response in the event of a tire fire.

Initial Site Stabilization

Large stockpile sites should be stabilized to decrease the possibility of a tire fire and to increase the odds of controlling a fire. Stabilization can be initiated by a site owner as part of a compliance agreement or by a contractor during the initial abatement. Important site stabilization activities include the following:

- Removal of trees, brush, and grass around stockpiles to avoid fire transmission to and from surrounding areas, especially if the site is inactive.
- Identification of available fire control resources and installation of supplemental fire control tools.
- Creation of at least two connected access points for emergency vehicles.
- Creation of fire lanes that are at least 15 meters (50 feet) wide to divide a large stockpile into isolated segments. The initial lane should roughly bisect the pile, and subsequent lanes should result in pile segments that are no larger than 15 by 60 meters (50 by 200 feet) in size. Pile sides should be tapered to avoid collapse during fire turbulence.
- Stabilization of central fire lanes to facilitate access by emergency response vehicles and to maximize contractor efficiency during subsequent abatement activities.

Site Abatement

During site abatement, alternate pile segments should be sequentially removed to increase separation between remaining segments.

Shred Auto-Ignition

Deep stockpiles of compacted tire shreds can undergo a progressive series of exothermic reactions that increase pile temperatures and pyrolytically generate combustible gases. Surface symptoms of this phenomenon can be subtle, such as a slight sulfur odor, vapor steaming from isolated sections of the pile surface, or slight oil sheen on adjacent standing water after rainfall. Auto-ignition normally occurs in stockpiles that are more than 10 feet deep and that have been compacted by movement of heavy equipment during their formation. The phenomenon has occurred in shreds of all sizes but is more common in smaller shred sizes.

The potential consequence of auto-ignition is that surface fires can ignite on a shred stockpile, especially as the pile is abated. As shreds are removed from the area near the hot zone, gases and shreds are exposed to air and ignite. The fire then spreads across the pile as though it was started on the surface, as has occurred in more than 20 stockpiles and monofills. A sign of this phenomenon is an area of melted rubber shaped like a mushroom cap within the pile. Care should be taken during abatement of deep, compacted shred piles, and steps should be taken to immediately control auto-ignited shred fires before they can spread.

Communication

Successful abatement of a stockpile site depends on good communication between the contractor and the contracting government department. Both efficiency and mutual respect are acquired from experience, which is critical to successful tire abatement projects and programs. On-site monitoring and invoicing are also important elements of communication, as discussed below.

Contractor and Government Department Communication

Abatement plans and schedules are working documents that are subject to change based on factors such as weather, equipment breakdowns, and market conditions. Good communication between the contractor and the contracting agency provides a foundation for appropriate adjustments. The contractor can provide a weekly, biweekly, or monthly written progress report describing tire quantities removed, adherence to the schedule, obstacles, adjustments, and anticipated future activities. Progress reports may also be made verbally at the department's discretion.

On-Site Monitoring

Performance monitoring is a balance of economics, need, availability, and experience. States have used full-time monitors, facilitated daily visits by local officials, reviewed logs kept by security, or contractor personnel, and conducted unannounced site visits and record audits.

Invoices

The contractor should submit monthly invoices with all supporting documentation. This procedure allows problems to be identified early and limits the amount of invoice preparation and review time.

Site Restoration

Abatement Completion

The issue of abatement completion is subject to interpretation when tires are buried on a site. In general, large pockets of tires are removed but individual tires are left in place if less than 25 percent of the tire extends above the surface. In cases involving tire shreds, some states require the contractor to use a 2-inch rake harrow to gather and remove surface shreds.

Other Wastes

Other waste materials present in tire stockpiles are normally separated and placed in piles. In some cases, wastes are segregated to facilitate subsequent recovery (for example, of metals) or disposal efforts. A contractor's responsibility for other wastes should be clearly defined in the initial scope description. The contractor should receive supplemental compensation for waste-related activities outside the scope.

Grading

A site can be deeply rutted by heavy equipment during abatement. The contractor is generally required to restore a relatively smooth surface corresponding to the original site contour.

Roadways

Public dirt roadways rutted by heavily laden trucks during abatement are generally graded at the end of on-site activities. County road crews are often assigned to this grading at little or no cost as a show of cooperation. Access roadways constructed to facilitate the abatement are sometimes removed.

Erosion Control

Seeding and drainage channels can control erosion of unstable surface soil. Silt screens or similar methods are used to control site runoff to adjacent surface waters until vegetation is re-established.

Documentation
Post-abatement site conditions should be thoroughly documented by means of photographs or video recordings of ground conditions, residual piles, buildings, and fences. The documentation should be retained to aid in resolution any subsequent problems or issues.

SUMMARY

Many states in the United States have successfully cleaned up scrap tire stockpiles and established programs to prevent future formation of stockpiles. Much can be learned from the successes and failures of the wide array of strategies used to address this serious problem. This chapter is an effort to capture and share the collective knowledge of U.S. state and industry representatives with decades of experience in stockpile abatement

Many U.S. states have demonstrated that the threats to human health and the environment posed by uncontrolled and illegal scrap tire stockpiles can be mitigated. This can be done through thoughtful application of regulatory policy and available resources along with careful planning and execution of cleanup projects. Based on the experiences of state and federal authorities in the U.S., the costs of stockpile prevention and abatement are small fractions of the costs associated with emergency response and remediation necessitated by tire fires.

This chapter has provided an outline of the essential elements that states have considered in planning and implementing abatement programs and individual cleanup projects. After decades of catastrophic tire fires and other health-related impacts of illegal scrap tire piles, it is clear that these practices can be effective in protecting human health and the environment from these hazards.

Large scale scrap tire pile fire
Photo courtesy of Todd Thalhamer, California IWMB

CHAPTER 3

Ground Rubber

Ground rubber, or crumb rubber, results from the size reduction of scrap tires or other rubber products. The processing of tires into ground rubber can be done by machinery to shred or grind them and sorting the resulting pieces which will determine its use. Additional processing may be necessary to remove all metal beading dependent on its intended market. After processing the resulting tire pieces generally range in size from about 40 mesh to about 6 cm (1/4 inch). Ground rubber can be used for a wide variety of products, ranging from animal mattresses and traffic cones to athletic surfaces and as additive to asphalt, each of which will be discussed in this chapter.

Within the traditional recycling hierarchy, the highest-value applications (the special uses to which scrap tires are put) for scrap tires use ground rubber itself for its specific performance characteristics. To maximize the value of scrap tire resources, tremendous financial, technical, and creative resources have been devoted to developing tire processing technology to make ground rubber and applications to use it. Results have been mixed, however. The Rubber Manufacturers Association estimates that, after more than 20 years of concerted effort, only about 17 percent of the waste tires generated in the United States in 2007 were processed into ground rubber for use in many creative applications (Ref.1). Since these applications have historically developed slowly and do not consume enough tires, they cannot be the primary focus of a new scrap tire management program. However, they remain a sound recycling option and an important component of market diversity.

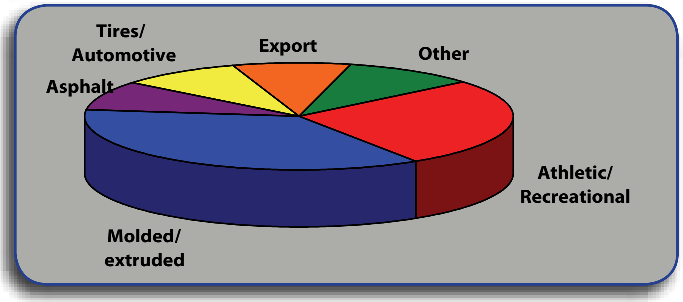


Exhibit 3-1. U.S. Ground Rubber Market Distribution
Source: Rubber Manufacturers Association

The energy and civil engineering markets are larger and can be developed more rapidly, so they deserve initial program focus to accelerate full use of waste tire resources. As a result, this guide focuses on these applications. However, major ground rubber markets can be identified and developed concurrently. In addition, with the experience gained in the United States, it may be possible to accelerate market growth in Mexico.

Initial development of civil engineering and tire-derived fuel (TDF) applications will not prevent ground rubber processors from obtaining scrap tires as needed in the future. As ground rubber markets develop, waste tires will naturally be diverted to products with higher value. Ground rubber products generate higher product revenue, allowing processors to attract waste tires by charging lower tipping fees. Waste tires generally move to the lowest-cost disposal or recycling option, so higher- markets like ground rubber naturally displace lower-value civil engineering and TDF markets.

MAJOR U.S. GROUND RUBBER MARKETS

Previous experience in the United States does not necessarily translate into future markets in Mexico. However, it can provide examples of applications that have a proven ability to be manufactured and a willingness by consumers to purchase, two critical components of market development. Applications for ground rubber are normally grouped into the following major market segments:

Athletic/recreational surfaces – Use in artificial sports turf, natural (grass) turf and playground cushioning to protect children when they fall.

Molded and extruded products – Many products, including mats, bumpers, and other creative products.

Rubber modified asphalt and sealants – Addition of ground rubber to asphalt binder to improve highway performance characteristics, including how long the road will last.

Tires/Automotive – Use of ground rubber from scrap tires in manufacturing new tires, in the rubber compounds used to retread worn tires, and in molded automobile parts.

Other (Primarily Coarse Rubber) – Ground rubber is used primarily as colored mulch in landscaping applications.

Export – Ground rubber sold to markets in Europe and East Asia from the United States.

The percentage of ground rubber used in each of the major market segments in 2007 is shown in Exhibit 3-1, based on estimates made by the U.S. Rubber Manufacturers Association (Ref. 1).

The following sections are intended to identify and briefly describe major market segments, focusing on those with the highest growth rate in the United States and the greatest potential for initial development in other countries, for example, Mexico.

ATHLETIC AND RECREATIONAL SURFACES MARKET

Athletic and recreational surfaces currently represent one of the largest and most rapidly growing markets for ground rubber in the United States. This market segment encompasses a wide variety of applications and additional variations within them. The following discussion briefly summarizes the two largest applications within this market segment: synthetic sports turf, and playground safety surfacing.

Synthetic Sports Turf

Natural grass is a traditional sports field mainstay, but increasing usage of limited grass fields leads to turf failure, athletic injuries, and unattractive appearance of the field. In addition, standing water during wet weather can prevent use of grass fields and damage the field. Good grass surfaces require routine watering, fertilizing, and turf replacement, resulting in significant maintenance costs. Damaged grass surfaces may contribute to injuries when the ground is hard, muddy, or loses traction. Awareness of costs associated with maintenance and injuries has led to development of alternatives.

Initial synthetic sports surfaces were developed for indoor arenas where the absence of sunlight prevented use of natural turf. One of the early examples was the Astrodome in Houston, Texas, which caused the trademarked name Astroturf to become a generic description for an early generation of artificial playing surfaces. More sophisticated systems that use ground rubber were developed in the 1990s to overcome some of the issues associated with the initial artificial surfaces. These advanced turf systems were initially applied in high-profile U.S. football stadiums used by professional and major university teams but are now in broad use on a wide range of sports fields at all levels of play.

Description

The current generation of artificial sports turf uses 7.6-cm (3-inch)-long strands of green polyethylene embedded in a porous backing to form a carpet-like structural framework for the turf system. The carpet is spread over a sophisticated drainage system capable of removing rain water rapidly and is in-filled with silica sand, ground rubber, or layers of each. A schematic representation of the FieldTurf Tarkett design is shown in Exhibit 3-2.

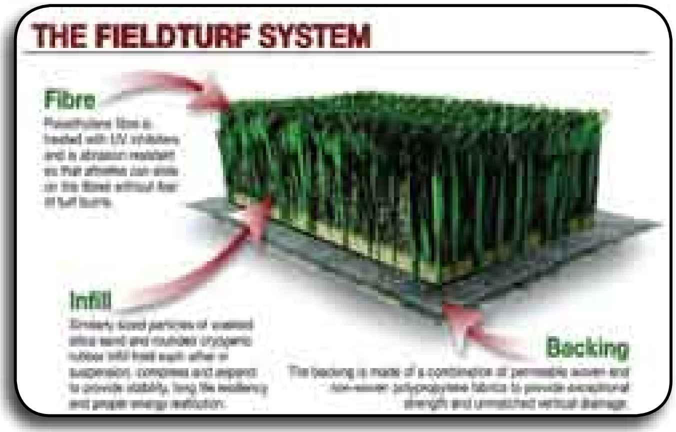


Exhibit 3-2. Field turf cross section
Photo courtesy of FieldTurf Tarkett

Berry Stadium, Cy-Fair Independent School District, Houston, Texas
Photo courtesy of Terry Gray, TAG

The result is an attractive turf that drains water rapidly and is capable of withstanding comparatively heavy use. The polyethylene grass-like blades add containment to the ground rubber, and the rubber provides cushioning while the combined synthetic turf system bears the physical forces of athletic activity. The backing — which holds the polyethylene blades, the blades themselves, the ground rubber,

Table 3-1. Partial List of Synthetic Turf Installations in Mexico

Project Name	City	Country	Year
Pyesa Tenis-TV Azteca	Monterrey	Mexico	R2003
Tec de Monterrey CEM	Guanajuato	Mexico	04/07/2008
Centro Asturiano de Mexico	Ciudad de Mexico	Mexico	09/25/2007
Centro Asturiano de Mexico-Field #5	Mexico City	Mexico	09/21/2007
Centro Asturiano de Mexico-Field #4	Mexico City	Mexico	09/21/2007
Centro Asturiano de Mexico-Field #3	Mexico	Mexico	09/21/2007
Mas Futbol Leon	Leon	Mexico	10/18/2006
Unidad Deportiva Valenciana-Field 2	Guanajuato	Mexico	06/07/2006
Unidad Deportiva Valenciana-Field 7	Guanajuato	Mexico	05/10/2006
Unidad Deportiva Valenciana-Field 1	Guanajuato	Mexico	05/10/2006
Unidad Deportiva Valenciana-Base ball	Guanajuato	Mexico	03/29/2006
Mario Castro Field-Sport 7	Queretaro	Mexico	01/24/2006
Soccer City Querataro-Field 2	Querétaro	Mexico	01/14/2006
Soccer City Celaya	Celaya	Mexico	01/05/2006
Soccer Society Aguas Calientes	Guanajuato	Mexico	12/15/2005
Roberto Pina Field	Guanajuato	Mexico	11/14/2005
Futura Soccer	Veracruz	Mexico	11/05/2005
Charrua Field	Charrua	Mexico	09/30/2005
Dinamo Irapuato Field	Irapuato	Mexico	09/12/2005
John F. Kennedy School-Tampico Field	Tampico	Mexico	09/02/2005
John F. Kennedy School-Main Field	Queretaro	Mexico	08/25/2005
Sportfield/AstroPlay Inventory	Mexico City	Mexico	N2003
Colegio Marcelina	Queretaro	Mexico	R2003
University of Toluca	Toluca	Mexico	R2003
Soluciones Industriales	Queretaro	Mexico	2007-2008
Perfect Tu Cancha	Guatemala City	Guatemala	2007-2008
Canchas Sinteticas	Tegucigalpa	Honduras	2005-2008

and other parameters of the turf system can be varied to achieve different performance characteristics for specific sports. Each manufacturer has variations intended to offer technical or economic advantages. An example of a U.S. football field is shown at the right.

Current Market Status

Synthetic sports turf has grown rapidly to an estimated 1,000 field installations in 2008 in North America and hundreds more in Europe, according to the Synthetic Turf Council (*www.syntheticturfcouncil.org*). These installations range from large stadiums to smaller municipal playing fields. The turf has been installed for international football, American football, field hockey, baseball, other sports, and practice facilities. The company FieldTurf Tarkett is one of the earliest manufacturers of synthetic sports fields and is believed to have installed more than half of these fields. Other companies with established roles in the sports field market include General Sports, IC Improvements, Sportexe, Sprint Turf, and other

Necaxa Soccer Club field in which ground rubber was used to create synthetic turf
Photo courtesy of FieldTurf Tarkett

significant participants. Many of these companies sponsor web sites identifying regional offices, representatives, and authorized installers.

A partial list of installations in Mexico is provided in Table 3-1. This list is not complete, but it indicates that there are more than 30 installations in major stadiums and venues in Mexico.

The Necaxa Soccer Club facility, installed in 2003 in Aguascalientes, Mexico, is shown below as an example. Some of these installations have been in place for more than 10 years, providing a base of local experience. Furthermore, some of the systems have been tested and approved by the Fédération Internationale de Football Association (FIFA, the International Federation of Association Football in Zurich, Switzerland) governing body for their grass-like performance.

Ground Rubber Requirements

Each of the major synthetic turf systems uses ground rubber as the primary infill material surrounding the green polyethylene blades. The type and size of the ground rubber vary depending on the turf manufacturer. Some use primarily cryogenic ground rubber produced by freezing shredded rubber before it is fractured in a high-speed hammermill, a machine that pulverizes the rubber into fine particles. The resulting product has smooth sides and tends to flow easily when applied to a sports field. Others use "ambient" rubber, produced in a series of shear and compression equipment at ambient temperatures. This product tends to have a more irregular surface shape with a more cohesive consistency. A "crambient" product made by a primary cryogenic process followed by secondary ambient processing to yield hybrid performance characteristics is also used.

Piece size requirements for ground rubber also vary by turf manufacturer. The most common distributions of piece sizes for sports fields are 14-30 mesh and 10-14 mesh. "Mesh" is a term used to describe size and is equal to the number of holes per inch that the material can pass through. The specifications also generally require removal of virtually all the reinforcing fabric and wire that is initially present in scrap tires. Experience has shown that proper quality control of the ground rubber is critical for proper performance of synthetic turf.

Approximately 3 pounds of ground rubber are generally used per square foot of synthetic turf, depending on the manufacturer, design, and desired surface characteristics. As a result, the estimated 1,000 new fields in North America with an average size of about 7,500 square meters (80,000 square feet) would be expected to use about 110 million kilograms (240 million pounds) of ground rubber in 2008. This amount represents continuing growth from the Rubber Manufacturers Association's estimate of 800 fields installed in 2007. It is also one of the largest individual ground rubber markets. Industry participants feel that the market has further potential for growth and has not reached maximum demand.

Application Benefits and Issues

Virtually any product has advantages and disadvantages, and questions are commonly raised about new products. Synthetic sports turf manufacturers claim their products offer the following advantages versus traditional grass turf:

- **Injury/Health** - Synthetic turf remains consistent under varying weather, use, and maintenance conditions. According to a National Collegiate Athletic Association (NCAA) study that compared injury rates during the 2003-2004 academic year, the injury rate during practice was 4.4 percent on natural turf and 3.5 percent on synthetic turf (Ref. 2). Other studies indicate that frequency of injury is similar for both surfaces, but that the severity of injuries is worse on natural grass turf. There are more head, neural, and ligament injuries on natural grass, while there are more epidural, muscle trauma, and temperature-related injuries on synthetic turf (Refs. 3, 4).
- **Economics** – Synthetic turf's higher initial cost is offset by reduced maintenance associated with water, fertilizer, pesticides, cutting, turf replacement, and manpower. In some cases, budget, knowledge, and the availability of labor may limit proper maintenance of grass fields.
- **Availability** – Traditional turf may not be used for play without sustaining expensive damage when it is wet, limiting use of these facilities. Conversely, synthetic turf drains rapidly, allowing use quickly after heavy downpours. In addition, synthetic grass turf can reportedly tolerate up to 3,000 hours of use per year, about four times more use than natural grass turf, allowing the fields to be used more heavily for different sports.

These factors have fueled its rapid growth. Some questions have also been raised about the synthetic turf system. The following is a brief discussion of major issues and the status or conclusions based on available data.

- **Elevated Turf Temperature** – The pieces of black rubber and colored synthetic turf blades absorb light energy and become warmer than ambient temperatures. Limited data report surface temperatures of 49° C to 65° C (120° to 150° F) on sunny summer days with ambient temperatures of about 35° C (95 to 100° F). Other surfaces also tend to exceed ambient temperatures, even cement roadways and light-colored sand on beaches. The New York State Department of Environmental Conservation conducted a study in 2009 indicating that surface temperatures of synthetic turf are warmer than natural grass or sand, but that differences in wet bulb globe temperatures that more accurately reflect actual heat stress were similar, with minimal impact on athletes (Ref. 5). Customer reactions have ranged from no concern to limiting use during peak temperature times or using a water spray to cool the surface before use (Ref. 3).

- **Metals Leaching** – Tire rubber contains zinc, sulfur, and small quantities of other materials that are naturally in the environment at concentrations greater than can be leached by water flowing through rubber (above the water table). These metals are within the vulcanized rubber (rubber which has been chemically altered to increase elasticity and decrease temperature sensitivity) polymer matrix, but can be leached from the rubber surface by water. Multiple studies indicate that these metals do not represent an acute or chronic health or environmental hazard under conditions likely to be encountered on athletic fields based on established scientific evaluation criteria (Refs. 5 through 11).

- **Organic Chemical Emissions** – Studies indicate that a range of organic compounds may be emitted onto or from the surface of ground rubber pieces. Detailed studies conducted in Europe concluded that these materials do not represent a significant hazard to players or spectators in outdoor sports arenas with synthetic sports turf (Refs 11 to 14). Maintaining a minimum air turnover rate within the normal building design range was suggested to limit exposure in indoor sports arenas. These studies were prompted by concerns raised in Europe in 2002. Athletic federations examined the data and decided that the surfaces with ground rubber were suitable for use by their athletes. The issue has been raised again in the northeastern United States. Additional reviews of available data have been prepared, generally reaching the same conclusions about safety and environmental concerns. A list of representative studies is provided in the reference section at the end of the ground rubber section (Refs. 15 to 23). None of these studies indicates that the thousands of surfaces in the United States or Europe have caused health problems in athletes or spectators. Some cite the need for additional data, especially practical data from actual field installations. The U.S. State of New York issued its report in May 2009 with its structured field tests, confirming the acceptability of this material and surface (Ref. 5). California is currently planning structured field tests to further broaden the available database (Ref. 24).

Playground Safety Surfaces

Sand, wood chips, and small gravel are commonly used as cushioning materials around playground equipment, but each has limitations. Wood chips deteriorate with time, causing loss of cushioning and requiring frequent addition of more wood chips. Sand and gravel are limited in their ability to absorb impact. The development of scrap tire processing technologies created products suitable for use in three alternative types of playground cushioning surfaces that have been accepted in the United States.

Description

The three playground cushioning alternatives involving ground rubber in different forms are: (1) loose fill, (2) pour-in-place, and (3) molded tiles. Loose fill, pictured in Exhibit 3-3, was the first playground safety material derived from

Exhibit 3-3. Loose fill ground rubber installation
Photo courtesy of American Rubber Technologies, Jacksonville, FL

scrap tires. It is simply ground rubber about 1 cm (3/8 inch) in size with virtually all of the reinforcing wire removed. Some loose fill is made from fabric-reinforced truck tires or off-road tires to be sure that no wire is present. It is spread under and around playground equipment. A 14-cm (6-inch)-thick layer generally provides protection for falls from critical heights of about 3 m (10 to 12 feet), about double the height for an equivalent thickness of traditional materials. The ground rubber loose fill is normally placed over a substrate that freely drains liquids with a wooden border to keep loose fill from spreading away from the playground area. Tires are black, but loose fill can also be colored before it is installed to improve the aesthetic appearance of the playground.

Pour-in-place installations at playgrounds, shown in Exhibit 3-4, use a polyurethane binder to bond ground rubber or buffings from tire retread operations into a protective surface mat 5 to 10 cm (2 to 4 inches) thick. The ground rubber and polyurethane binder are commonly mixed on site in a portable cement mixer and then trowelled into place. A surface layer of colored ethylene-propylene-diene monomer (EPDM) rubber is generally bonded to the ground rubber base to provide distinctive colored surface patterns or pictures. Pour-in-place is normally installed over a hard surface such as asphalt to provide a stable foundation. The installation should be designed and tested to provide fall protection from heights associated with the various equipment at the playground.

Ground rubber can also be molded into thick interlocking tiles specifically designed to provide protection from falls. The tiles, shown in Exhibit 3-5, are typically 1/3 to 2/3 m (1 to 2 foot) squares and 5 to 10 cm (2 to 4 inches) thick and are commonly glued to a hard sub-base such as asphalt. Each tile is designed and manufactured to provide a durable surface that meets specific cushioning specifications.

Exhibit 3-4. Pour-in-Place Installation
Photo courtesy of Calgary, Canada, Parks and Recreation

Exhibit 3-5. Interlocking Tile Installation
Photo courtesy of Calgary, Canada, Parks and Recreation

Current Market Status
All three of these ground rubber products for cushioning playgrounds have been broadly used, but no published market data define the specific quantities of ground rubber used annually for these installations. It is substantial, but not growing rapidly. Many states have encouraged use of these products through cost-sharing grants, but volumes have been limited outside of these special programs. California, Florida, Kentucky, and Illinois are among the states that have aggressively promoted this application.

Loose fill is the least expensive to install. It has been widely used in Florida and Kentucky. The primary cost is the ground rubber itself, plus preparation of the base under the loose fill and the border around the perimeter of the area that will contain the ground rubber. Initial cost is generally more expensive than wood chips, but ground rubber does not degrade, so the annual replacement cost is lower. All loose playground cushioning products must be periodically re-leveled to maintain the desired thickness under and around equipment.

The total installed cost of pour-in-place and tiles are typically four to 10 times more than loose fill because of base preparation, the expense of binders, and labor for installation. Pour-in-place and tiles have been used extensively in California and Florida under state government grant programs that foster market development, but have seen limited use outside of these programs.

Ground Rubber Requirements
A range of ground rubber piece sizes is used in each of these playground surfaces. Manufacturing appropriate sizes for loose fill is controlled by the

need to separate and remove virtually all reinforcing wire from the scrap tire to avoid puncture wounds or injury. It is normally ½ to 1¼ cm (¼ to ½ inch) in size and is sometimes produced from fabric-reinforced truck tires or off-road farm tires that do not contain fine reinforcing wire to minimize potential residual wire in the product. Heavy bead wire around the rim of a tire is removed by debeading equipment before tires are processed or by magnets after processing. The material must be free of particles smaller than 20 mesh to minimize dust generation and small particles that cling to skin and clothes like dirt. Residual fluff from reinforcing fabric in tires is sometimes left in the ground rubber; it may improve resiliency, but it may also decrease the flash point of the mixture and allow it to be ignited by vandals more readily.

Pour-in-place and tiles generally use 3 to 10 mm (3/8 to 1/8 inch) ground rubber. In both cases, the fabric is removed to improve the efficiency and effectiveness of the binder, and the wire must be removed to minimize scrapes and cuts. A layer of colored synthetic rubber, known as EPDM (ethylene propylene diene Monomer rubber) or M-class rubber is commonly added to the ground rubber surface to add color and enhance surface aesthetics. Light colors can decrease light absorption and lower the surface temperature in warm weather.

Application Benefits and Issues
Durability – Rubber is flexible, resilient, and durable, properties that make it a good outdoor cushioning material. Some loose-fill playgrounds have been in place for more than 10 years with minimal need to add more ground rubber to replace material lost. The longevity of pour-in-place and tile surfaces is controlled by the effectiveness of the installation, binder, foundation, and usage, but manufacturers typically project a duration of more than 5 years.

Accessibility – Accessibility of equipment by children in wheelchairs or on crutches can be an important consideration. Loose fill's excellent cushioning characteristics also make it less stable under point loads such as wheel chairs, but some products have reportedly passed tests that demonstrate accessibility. Pour-in-place and tiles have excellent accessibility, so some playgrounds use them for access pathways and around some of each equipment type to assure access. Loose fill is used in other areas to control cost.

Flammability – Tire rubber has a flash point of more than 290° Celsius (550° Fahrenheit), higher than dry wood chips, and so is not readily ignitable. Fires have occurred in loose-fill installations, but there were no injuries or environmental damage other than the initial smoke. The California Department of Resources Recycling and Recovery (CalRecycle) documented a detailed examination of one playground fire site and found no residual environmental damage (Ref. 26).

Application Public Health Benefits and Issues
Latex Sensitivity – A small percentage of people are sensitive to the latex present in some types of rubber. CalRecycle tested for latex sensitivity in styrene-butadiene rubber (SBR) derived from scrap tires as part of its comprehensive review of ground rubber playground surfacing. The testing showed no sensitivity using established testing procedures on SBR and EPDM ground rubber, and no documented cases were found in a literature search (Ref. 22).

Toxicity – Toxicity and environmental questions associated with ground rubber have been raised for playground applications as well as for synthetic turf, with the same general conclusions as previously discussed. CalRecycle's detailed report addresses many of these concerns. It (1) identified no issues that would preclude using the superior cushioning characteristics of ground rubber on playground safety surfaces and (2) fully recognized the benefits of reducing injuries through use of ground rubber. The report is titled "Evaluation of Health Effects of Recycled Waste Tires in Playground and Track Products" (Ref 22) and is available on the CalRecycle web site at *www.calrecycle.ca.gov*.

Impact Cushioning – The primary objective of playground safety surfacing is reducing the impact of falls from equipment, and all three of these alternatives can serve this function as well as, or better than, natural materials when properly installed and maintained (Ref. 24). The U.S. Consumer Product Safety Commission has prepared a guide that provides detailed data and discussion of safety parameters for playgrounds, including surfaces. It is available on the web site at *www.cpsc.gov* as Publication 325, titled "Handbook for Public Playground Safety."

MOLDED AND EXTRUDED PRODUCTS

Molded or extruded products can be created when heated rubber is pressed into a mold or through a die cast to shape it into a new product. This market is very versatile and can create a wide variety of products ranging from pet toys, car bumpers, gaskets, and garden hoses to complex components for medical and electrical equipment.

Molded and extruded products are the second-largest application for ground rubber from scrap tires based on market data compiled by the Rubber Manufacturers Association (Ref. 1). These products represented 36 percent of ground rubber usage in the United States in 2007. This market is continuing to grow. It is a diverse market in terms of products and manufacturing technology and may have significant potential applicability in Mexico. The objective of this summary is to identify major product categories and technologies, and then provide references for additional depth.

Description

Molded products have been made from buffing dust (rubber particles removed from a tire carcass during retreading) for many years, but the range of products and the size of the markets have expanded significantly in the past 5 to 10 years. Three primary technologies are used to produce products that use ground rubber by itself or in blends with other materials. The following is a brief discussion of these technologies.

Sample of molded rubber traffic cone
Photo courtesy of Candy Lee

Molded Products

Many initial products were relatively small molded parts such as wheels for trash cans. There are many variations in molding technology, all using a similar basic process. A primary raw material or mixture is pretreated to allow it to flow into a mold where the material is cured, cooled, and released from the mold to yield a solid designed shape that meets defined specifications. Pretreatment can involve heat, mixing, and additives to create a semi-viscous homogeneous raw material. Once it has been introduced into the mold, temperature, pressure, and reaction time allow the material to solidify. There are also broad variations in degree of automation, balancing capital and labor costs for a specific operating environment. This basic technology has been fully demonstrated with many polymers and rubber materials, including mixtures with ground rubber. Each component of the process requires experimentation to optimize efficiency and product quality. This technology can be labor intensive in its basic form, making Mexico's labor economics potentially attractive to the manufacturing of these products as well as to increasing employment.

One example and potentially viable market that uses this process is the production of traffic cones (also known as road cones, safety cones, or pylons). The cone base is produced through compression molding of ground rubber obtained from scrap tires. The cone portion is made from recovered plastic material. The recycled materials content can range from 50 to 100 percent, depending on the production process, making these products environmental friendly. More information on the use of ground rubber in traffic cones can be found on line at *www.epa.gov/epawaste/conserve/tools/cpg/products/cones.htm*.

Bound Systems

Bound or bonded rubber products generally refer to use of polyurethanes, sulfur, latex, or other ingredients to bond particulate materials into a desired product. This is sometimes done using pressure and temperature to increase density or optimize efficiency. This technology was initially used on large, low-volume products such as railroad crossing fillers and speed bumps. With improved binders and product creativity, a broad range of higher-volume products have been produced and marketed successfully. The initially simple welcome mats using bound ground rubber evolved into attractively designed mats with mass market appeal, becoming a major consumer of ground rubber. Other mats gained acceptance in agricultural, recreational, and building applications. For instance, mats placed in livestock areas have been shown to increase milk production in dairy cattle and enhance weight gain in beef cattle. This provides an economic driving force for this large, established market segment in North America.

The playground safety tile discussed in the preceding section is an example of a bound product. A newer developing market uses thin sheets of bound ground rubber as carpet cushioning and sound deadening in residential apartments and houses. This product is sometimes made by peeling a thin layer off of a large bound rubber cylinder; efficiently producing a long roll of ½ to 1 cm (¼ to ½ inch) thick rubber matting that is easily transported and installed. It can also be manufactured as sized sheets.

Many binders have been used, but polyurethanes and sulfur are the most common. Sulfur is considered more durable and suitable for ultraviolet (UV) exposure in outdoor applications. Some types of polyurethane are able to tolerate UV, and coloring can be used in these products to shield the polyurethane binder from UV exposure.

Hundreds of products have been made using bound ground rubber, representing both small and large markets. Some products and processes are simple while others have necessarily become more sophisticated to meet specifications or to achieve the efficiency required to compete in the marketplace. A good understanding of existing products, performance requirements, processing technology, and economics is critical to developing these applications successfully. It typically takes a committed effort over a period of time to be successful.

Extrusion
Long items such as hoses, weather stripping, tubes, molding, and belting are commonly made by extrusion processes. There are also many variations of this technology, but it normally involves using a screw system to mix, heat, and force a raw material through a die to produce a continuous shape. This process is sensitive to multiple parameters and requires fine mesh ground rubber (30 to 200 mesh). Any residual wire or fiber can accelerate wear or damage extrusion heads and equipment. Extrusion may have greater future applicability for using mixtures of ground rubber and plastics to produce high-volume products such as synthetic wood, shingles and other structural materials.

Ground Rubber Requirements

Ground rubber specifications for this market segment depend on the process, product, and economics. Desired product characteristics control the size requirements for ground rubber pieces used in these applications. Larger piece size reduces binder requirements and retains the characteristics of rubber, but the resulting product has less bonding strength and coarser surface texture. Playground safety tiles are an example of an appropriate use of about 0.5 cm (¼ inch) ground rubber. Finer particles (10 to 40 mesh) require more binder, with its associated strength, and yield a smoother surface that can approach virgin materials. Wheels and vehicle mud flaps are two examples of products that require such fine particles.

Economics also play a role in rubber selection. The cost of ground rubber generally increases with decreasing piece size, and binders are generally much more expensive than the ground rubber. As a result, products made with finer rubber and more binder generally are more expensive. Ultimately, the product must compete cost-effectively in the market to be successful.

Application Benefits and Issues

Low-Cost Raw Material

Ground rubber can be a low-cost raw material with many of the intrinsic performance properties of rubber. The creativity and technology applied to its use have increased market diversity and volumes. This trend is expected to continue as costs of virgin raw material escalate.

Displacement Challenges

Making any new product can involve substantial investment in processing technology, equipment, optimization, product testing, distribution, and marketing. All require time and resources that are often underestimated. Incorporating ground rubber into an existing formulation can pose similar challenges, especially in process optimization and product testing.

Mixtures

Rubber generally functions as filler in mixtures with plastics. Thermoset rubber and thermoplastics do not naturally bond, resulting in significant changes in the performance characteristics of plastics when rubber is added. Impact resistance normally increases, but other critical properties such as tensile strength and elongation decrease significantly, thereby decreasing the strength of the resulting product. Broader applicability of these mixtures hinges on identification of products where impact resistance dominates other performance requirements or on development of economically viable rubber surface modification technology that will allow the materials to bond. Extensive research has been devoted to this subject with some success in reducing property deterioration, but the resulting products have rarely competed successfully with alternative virgin materials. However, the increasing cost of hydrocarbon-based polymers and virgin rubber may provide additional incentive to further develop this technology or for manufacturers to tolerate moderately reduced performance.

RUBBER MODIFIED ASPHALT

Rubber modified asphalt is the product of mixing crumb rubber from scrap tires or other sources with asphalt. This can be done at varying rubber to asphalt ratios dependent on its intended use. Initial rubber modified asphalt technology was developed more than 30 years ago, has been actively promoted for at least the past 20 years, and has continued to evolve. The McDonald patents have expired, and this technology is now commonly referred to as the Arizona Process because of its extensive use within Arizona. Variations have been developed in an effort to address perceived obstacles or improve performance. In each case, rubber is mixed with the asphalt binder. The asphalt binder is then mixed with the aggregate and spread on the roadway to form asphalt pavement. This technique is commonly known generically as the wet process because rubber is mixed with the asphalt binder first.

Description of Technologies

The following is a brief description of the three major rubber modified asphalt technologies:

Arizona Process

The Arizona process involves mixing and reacting rubber with asphalt binder in specialized equipment at the paving site. Ground rubber normally represents about 20 percent of the asphalt binder mix, significantly increasing the viscosity of the binder. Greater viscosity allows a higher concentration of binder to be used in the asphalt mix, resulting in a stronger and more durable pavement. Use of rubber, more asphalt binder, and specialized on-site blending equipment increases unit cost/ton of asphalt 25 to 100 percent above traditional asphalt, depending on location, job size, and other job-specific criteria. In some cases, increased pavement strength has allowed thinner rubber modified asphalt overlays to demonstrate life comparable to thicker traditional asphalt, so that the installed cost of rubber modified asphalt is comparable.

Terminal Blending

Terminal blending involves blending rubber into the asphalt binder in a mixing tank at the asphalt supply terminal, then transporting it to the job site, thereby reducing the need for specialized equipment at the site. The terminal blending mix must be continuously mixed to keep the suspended rubber from settling out prior to transport. Rubber usage levels are specified to meet design performance characteristics for the pavement. This technology has been used for 15 years in Florida with a good performance history. Florida was the only state to specify rubber modified asphalt for friction course replacement on most state-maintained, high-traffic roads, including interstate highways. The technology is gradually being used more widely in other states such as California because of its lower cost.

Rubber/Polymer Blends

Styrene-butadiene-styrene (SBS) block copolymers are also used as additives in asphalt to improve performance. However, proponents believe that addition of a combination of both the SBS block copolymer and rubber to the asphalt enhances the performance more than either material can when they are added separately. This technology has been broadly applied in Texas and other U.S. states by using variations of the compounds, depending on the geographic area of application. The Florida Department of Transportation (DOT) is conducting a comprehensive evaluation of several polymer/rubber technologies compared with traditional asphalt. The technology uses a low percentage of rubber to partially displace normal polymer addition levels. This technology is the newest, but it is rapidly developing a substantial experience and testing base.

The availability of rubber, polymer, and rubber/polymer blend technology is also playing a role in development of pavement design alternatives that can reduce road noise levels and improve the safety of highways. Noise reduction and increased safety are accomplished through use of open-graded friction course (OGFC) pavement using large, uniformly graded aggregate. Rainwater flows through the resulting top layer of pavement (the friction coarse) and out to the sides of the roadway. This reduces hydroplaning and enhances driver visibility through a reduction in water spray from the vehicle tires. The open structure also creates an acoustic surface that absorbs and deflects some sound and reduces road noise for nearby residents. Experiments are under way to determine if the noise reduction levels will allow long-term use of this pavement as an alternative to expensive and unattractive noise barriers along highways through populated areas. Arizona and California are actively using this material, and other states such as Texas are using OGFC for safety reasons on historically dangerous roads. Enhanced binders play a critical role in allowing OGFC to maintain its long-term integrity, and rubber contributes to sound reduction.

Current Market Status

Rubber modified asphalt is the third-largest application for ground rubber in the United States. It represents 9 percent of the ground rubber market or less than 2 percent of the annual scrap tire generation in 2007, according to the Rubber Manufacturers Association (RMA) (Ref. 1). More than 90 percent of the rubber modified asphalt is currently used in Arizona, Florida, Texas, California, and South Carolina. Many other states have conducted trials or trial programs, but their use of rubber modified asphalt remains small. In addition, the Provinces of Alberta and Ontario in Canada have conducted thorough test programs. Still, total use of ground rubber in this application has not grown significantly in the past 5 to 10 years. Reduced paving and cost consciousness caused by transportation departments' budget constraints have contributed to limited growth.

Ground Rubber Requirements

Each state in the United States has established its own ground rubber specifications with variations for alternative applications. The Arizona process typically uses 16-30 mesh ground rubber with low limits for residual wire and fiber. Terminal blending in Florida initially used fine-mesh, such as minus 80 mesh (the minus implies that it is finer than 80 mesh since material has passed through a 80 mesh screen) ground rubber, but found that minus 40 mesh performed well with lower cost and better availability. Polymer/rubber blends vary widely, with some technologies pre-treating the rubber to enhance its reactivity in the asphalt.

Application Benefits and Issues

Performance

Roads using the Arizona and terminal blend processes have been documented to last longer than traditional asphalt, sometimes dramatically longer, but this performance has not been universal. Poor performance has been attributed to improper installation, weather conditions, bed preparation, and aggregate grading. Florida found that rubber modified asphalt performed well, but that polymers out-performed terminal-blended rubber modified asphalt for some high-traffic applications. This finding prompted interim modification of specifications to allow use of polymers and initiated Florida's previously referenced research into polymer/rubber blends. Tests in Alberta found variations in performance, some probably attributable to the initial learning curve.

Cost

The installed cost of an equivalent thickness of rubber modified asphalt is generally 10 to 100 percent higher than unmodified asphalt, as previously discussed. Since transportation departments' budgets are fixed, higher cost forces less paving and can cause short-term problems even if it has long-term benefits. Use of thinner rubber modified asphalt lifts (layers) can turn cost into an advantage where applicable and accepted.

Cost Justification

As the public becomes more aware of the safety and noise advantages of OGFC, the cost comparison should appropriately be broadened to include other avoided costs such as accidents and sound barriers. In that case, the comparison is not with traditional asphalt, but instead is with alternative OGFC mixes, and rubber modified asphalt is a proven material in these applications.

Horse arena using ground rubber surfacing
Photo courtesy of American Rubber Technologies, Jacksonville, Florida

Ground rubber used to create mulch
Photo courtesy of American Rubber Technologies, Jacksonville, FL

Ground rubber mulch
Photo courtesy of American Rubber Technologies, Jacksonville, FL

Ground Rubber Quality
The quality of the ground rubber is a critical performance factor in rubber modified asphalt. Ground rubber processors must recognize and consistently meet applicable product specifications. Failure to do so places the pavement at risk and alienates transportation departments and their installation contractors.

OTHER MARKETS

There are many smaller markets for ground rubber. Some are variations of the major markets discussed above, while others are unique niche products, and a few offer significant potential for growth. The following is a brief discussion of some of these products:

Horse Arena Cushioning

A variation of loose fill used as playground safety cushioning, ground rubber serves a similar function in horse arenas. It provides similar protection for horses and riders during practices and exhibitions. It also reportedly enhances footing and reduces stress on the horse's legs and joints. The material must meet defined specifications to balance sure footing with impact safety. This small, useful, and stable market may offer significant market potential to Mexico.

Animal Mattresses

Coarse ground rubber is used as filler in fabric mattresses that provide an alternative to the molded and bonded products discussed earlier. They are used primarily in the dairy industry to reduce leg injury, enhance comfort, and provide protection for utters of milking cows, which can increase milk production. Research has shown that rubber-filled mattresses last longer, as they do not compress as quickly and they are preferred in extreme temperatures (Ref. 26). It uses less than 3 percent of the current ground rubber stock and is a market that shows growth potential, according to the U.S. Rubber Manufacturers Association (Ref. 1).

Colored Mulch

Wood mulch is commonly spread around plants and flower beds to retain moisture, control weeds, and enhance beauty of the beds. However, mulch decomposes, harbors insects, and requires frequent replacement. Initial experimentation with black tire chips found that they controlled weeds much like wood chips and stayed in place, but the black color absorbed heat and had limited aesthetic appeal. Extensive experimentation led to relatively simple methods to color chips with paint that adheres and resists fading to assure warranted performance for 5 years or more.

Today's colored mulch is 1 - 2.5 cm (3/8 to 1 inch) chips made from scrap tires with 99 percent of the reinforcing wire removed. It is manufactured in many pleasing colors to simulate wood chips or to provide coordinating and contrasting colors. It has been shown to control weeds, resist mold, retain moisture, and require infrequent addition. As added benefits, it does not harbor insects or attract neighborhood animals.

Some issues have been raised about the use of colored mulch, as discussed below:

Flammability
Limited tests have shown that colored mulch has an ignition temperature above 290° Celsius (550° Fahrenheit), so flammability is comparable to dry wood chips.

Temperature
Black ground rubber pieces absorb light and can heat up. Colored mulch does not absorb as much energy thereby reducing the temperature increase.

Zinc Leaching
Tire rubber contains about 1.5 percent zinc as a vulcanization accelerator within the rubber polymer matrix. Water can gradually leach small amounts of zinc from the chip into the underlying soil. Traces of zinc serve as a micronutrient for many species, but excessive quantities can have a negative impact on some plants and grasses. Leaching is slow and controlled with water flowing through chips on the surface of beds, but it could be accelerated by continuous submersion in water or soil. Therefore, colored mulch should be kept on the bed surface and not mixed with soil. Coloring the mulch limits chip

surface exposure to moisture and further reduces possible leaching.

Rubber mulch was initially sold in small quantities through nurseries, landscapers, and specialty shops. However, it is becoming an established product with increasing representation in major high-volume retailers throughout the United States. If current growth rates continue, colored rubber mulch could become a large, high-value market for small scrap tire chips.

SUMMARY

Ground rubber products embody the creativity and expertise that have been developed to constructively make use of scrap tire resources. Although it may be desirable to use all scrap tires in these and similar applications, it has taken many years to reach 17 percent of annual scrap tire generation. These products can be an important long-term component of scrap tire use, while initial market development efforts focus on energy and civil engineering applications to maximize short-term use of this resource.

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CHAPTER 4

Energy Utilization

Scrap tires are a resource. The cornerstone of an effective scrap tire management program is developing diverse applications, or purposes for which to apply this resource, preferably ones that (1) can be developed reasonably quickly; (2) use large quantities; (3) are technically and environmentally sound; and (4) are economically feasible and sustainable. The largest application in the United States, Europe, and Japan, among others, is using scrap tires as a supplemental energy resource.

Scrap tires have been used for energy in Japan, Europe, and the United States since the 1970s. Paper manufacturing mills began using tire-derived fuel (TDF) in the United States in the late 1970s. The experience base has broadened significantly during the last 10 to 15 years as tires have become recognized as a viable alternative fuel in appropriate combustion processes. Once a tire is in a scrap tire pile, its uses are limited but it is still a viable option for energy utilization. Applications include cement kilns, industrial boilers, utilities, and dedicated electrical generation facilities. In 2007, 123 permitted facilities used 155 million waste tires as fuel in the United States, according to a market analysis conducted by the U.S. Rubber Manufacturer's Association (RMA) (Ref. 1). This volume represents almost 2.3 million metric tons (2.5 million U.S. tons) or 54 percent of scrap tire generation.

The following sections discuss the energy and chemical characteristics of tires, as well as historical experience in major energy applications. The objective is to assist governments and industries in evaluating and developing these uses as part of evolving tire management programs in Mexico and the United States.

CHEMICAL CHARACTERISTICS OF SCRAP TIRES

The chemical characteristics of any energy resource affect its technical and environmental performance. Tires are a hydrocarbon-based material derived from oil and natural gas. Some inorganic materials are added to enhance vulcanization reactions or performance properties, such as flexibility and resistance to UV light. Tires have a heat content of 14,000 to 15,500 British thermal units per pound (Btu/pound) (7,800 to 8,600 kilocalories per kilogram [kcal/kg]), depending on the type of tire and the amount of reinforcing wire that has been removed. By comparison, another solid fuel commonly displaced by use of tires as an energy resource is coal that typically contains 10,000 to 13,000 Btu/pound (5,550 to 7,200 kcal/kg).

Tires can be used whole in some applications, such as cement kilns. Others require tires to be shredded into smaller chips called TDF, with reinforcing bead and cord wire removed if necessary. Regardless of particle size, tires remain a solid fuel. Applicable systems must be able to receive and combust solid fuel to be a candidate for use of TDF. The energy from TDF can replace higher-cost oil and gas in some cases where oil, gas, and solid fuels are co-fired in the same furnace.

The composition of tires and coal vary, depending on type and source. However, Table 4-1 provides representative proximate and ultimate analysis of TDF with about 90 percent of the reinforcing wire removed and of a bituminous coal used to generate steam. Proximate analysis defines basic combustion characteristics. Ultimate analysis defines elemental composition.

A comparison of the proximate analysis indicates that tires offer efficiency advantages versus coal. For instance, tires generally have lower moisture content than coal. Since energy required to heat and vaporize water is generally non-recoverable in the energy conversion process, lower moisture content can translate into higher combustion efficiency. TDF is 1 to 3 percent more efficient than the coals cited in Table 4-1 because of its lower moisture content. The lower ash content of TDF (without wire) offers a similar advantage versus coal and can decrease ash disposal costs. A tire's higher volatile-to-fixed carbon ratio enhances its ability to combust rapidly and completely. TDF's advantages become commanding when compared with some of the high-ash, low-Btu coal and lignite. Based on proximate analysis, tires compare favorably with coal as an energy source.

Based on ultimate analysis, tires offer some additional advantages and disadvantages. When compared with many Eastern U.S. coals, TDF's lower sulfur content (especially in terms of pounds per million Btu) offers

Table 4-1 Comparative Chemical Characteristics

CHARACTERISTIC	BITUMINOUS COAL -NORTHEASTERN U.S.	TDF (90+% WIRE REMOVED)	SUBBITUMINOUS COAL - WESTERN U.S.
MOISTURE (% AS RECEIVED)	10.43	0.62	24.68
HEATING VALUE (BTU/ POUND, AS RECEIVED)	10,641	15,404	9,287
PROXIMATE ANALYSIS (%, DRY BASIS)			
ASH	16.16	4.81	6.37
VOLATILE CARBON	38.14	67.06	44.43
FIXED CARBON	45.70	28.13	49.20
TOTAL	100.00	100.00	100.00
ULTIMATE ANALYSIS (%, DRY BASIS)			
CARBON	65.49	83.79	70.73
HYDROGEN	4.56	7.13	4.85
NITROGEN	1.11	0.24	0.84
SULFUR	4.52	1.84	0.41
ASH	16.16	4.81	6.37
OXYGEN (by difference)	8.16	2.18	16.80
TOTAL	100.00	100.00	100.00
ULTIMATE ANALYSIS EXPRESSED AS POUNDS/MILLION BTU			
CARBON	55.13	54.05	57.36
HYDROGEN	3.84	4.60	3.93
NITROGEN	0.93	0.16	0.68
SULFUR	3.81	1.19	0.33
ASH	13.61	3.12	5.17
OXYGEN (by difference)	6.87	1.42	13.62
SUBTOTAL	84.19	64.54	81.09
MOISTURE	9.80	0.40	24.68
TOTAL	93.99	64.94	105.77

the potential advantage of decreasing emissions of sulfur oxide gas compounds referred to as SOx. However, the sulfur content of many Western U.S. coals is lower, so sulfur oxides must be controlled within these systems to prevent an increase with TDF.

Combustion systems burn less of a high-energy fuel to obtain the same energy, so expressing the ultimate analysis as pounds per unit of energy such as million Btu identifies some other important environmental factors. Combustion of TDF generates less carbon per million Btu than either coal cited in Table 4-1. Since carbon converts to the greenhouse gas carbon dioxide (CO_2) during combustion, TDF reduces emissions of this greenhouse gas compared with these coals. TDF also has a higher hydrogen content. When hydrogen combines with oxygen during combustion, it releases energy and forms water (H_2O) with no greenhouse gas, so energy released from hydrogen combustion also decreases formation of greenhouse gas compared with carbon. Therefore, TDF's lower carbon and higher hydrogen content on an energy basis results in lower greenhouse gas generation. In addition, TDF's lower nitrogen content can marginally decrease emissions of nitrogen oxide compounds called NOx.

The chlorine content of tires is higher than some coals and comparable to other coals. In addition, the chlorine content in tires has been significantly reduced in many newer tires, as the chlorinated butyl inner liner has been replaced by alternative materials.

Table 4-2 Elemental Metals Analysis

ELEMENT (OXIDE)	BITUMINOUS COAL -NORTHEASTERN U.S.	TDF 90% (WIRE FREE)	SUBBITUMINOUS COAL WESTERN U.S.
MAJOR OXIDES, AS % OF ASH			
Aluminum (Al_2O_3)	19.10	<0.01	18.10
Calcium (CaO)	5.18	0.38	13.50
Iron (Fe_2O_3)	20.40	0.32	4.90
Magnesium (MgO)	0.82	<0.01	4.52
Phosphorous (P_2O_5)	0.17	<0.01	0.36
Potassium (K_2O)	1.87	<0.01	1.01
Titanium (TiO_2)	0.89	<0.01	1.20
Silicon (SiO_2)	49.20	0.52	36.20
Sodium (Na_2O)	0.71	<0.01	5.55
Sulfur (SO_3)	1.60		13.40
TRACE ELEMENTS, PARTS PER MILLION WITHIN COAL OR TDF			
Silver	0.02		0.02
Arsenic	4		1
Barium	43	ND	694
Beryllium	1.3		0.2
Cadmium	0.02	0.0006	0.02
Chlorine	1200	0.149	900
Chromium	21	0.0097	5
Copper	10		13
Mercury	0.05		0.04
Manganese	62	<.01	18
Nickel	14		1
Lead	15	0.0065	4
Rubidium	15		4
Selenium	1		1
Silver	0.02		0.02
Strontium	41	<0.1	348
Vanadium	3		15
Zinc	97	1.52	8
Zirconium	26		22

Elemental ash analysis provided in Table 4-2 indicates that tires generally contain metals at concentrations comparable to, or lower than, coal, with one notable exception. Zinc is added to tires as part of the rubber vulcanization process at levels approaching 1.0 to 1.5 percent by weight. Therefore, zinc levels in tires are much higher than in coal. Applications that use tires as an energy resource must therefore be able to control zinc emissions to avoid a negative environmental impact. Common air pollution control equipment such as electrostatic precipitators and baghouses effectively control zinc oxide emissions from TDF combustion.

From a chemical standpoint, tires offer both environmental advantages and disadvantages versus coal. Therefore, tires provide a valuable and environmentally friendly energy resource when used in applications that draw on their advantages and properly control their disadvantages.

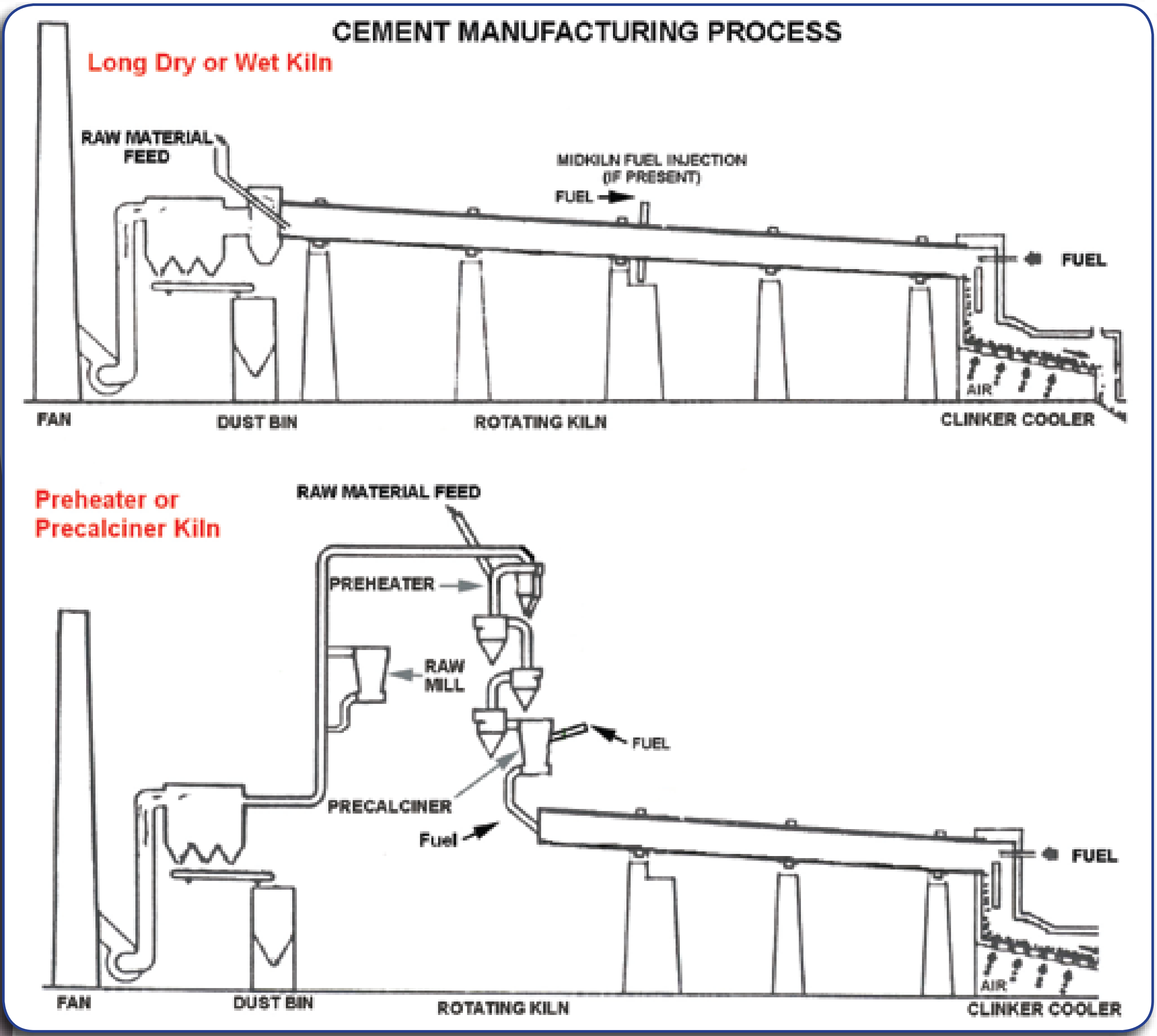

Exhibit 4-1. Cement manufacturing process
Source: Portland Cement Association

CEMENT KILNS

Scrap tires have been used as a supplemental fuel in cement kilns in Europe and Japan since the 1970s. It also currently represents one of the largest applications in North America. Only one cement facility in the United States (then called Calavaras Cement in California) consumed waste tires 20 years ago. In 2007, 43 cement facilities used either shredded or whole tires as a supplemental energy source in the United States, according to the U.S. RMA (Ref. 1). These facilities consumed nearly 607,000 metric tons of TDF, representing about 44 million scrap tires. Others are conducting performance tests targeted at future use. Sixteen cement companies own these facilities, including the largest North American, Latin American, and global cement producers. Broad corporate experience enhances transfer in this technology for additional facilities and accelerates internal evaluation and implementation.

Basic Process

Cement manufacturing technology has evolved, but the basic process has changed little. Major processing steps include the following:

- **Raw material preparation:** Major raw materials are crushed and blended in proper proportions, including limestone ($CaCO_3$), shale or clay (Al_2O_3 and other compounds), sand (SiO_2), and iron (Fe_2O_3).
- **Thermal processing:** Fuel is combusted at the firing end of the kiln, generating gas at temperatures in excess of 1,650°C (3,000°F) that travel through the processing equipment. The

Exhibit 4-2. Mid-kiln injection
Source: North Texas Cement

raw material mix is introduced into the opposite feed end of the process. Moisture is evaporated initially, and the mix is ultimately heated to 1,450°C in the burning zone as it travels toward the firing end of the kiln. The raw material mix undergoes a series of reactions that transforms the solid particles into a liquid and allows creation of the calcium silicate agglomerates about 2.5 cm (1 inch) in diameter, referred to as clinker. The clinker is cooled rapidly as it leaves the firing end of the kiln. The chemical composition of the raw mix must be carefully controlled to yield clinker with the required chemical and physical properties.

- **Cement production:** Clinker is ground and combined with gypsum and other inorganic materials to form cement that meets the defined performance specifications.

Alternative Kiln Types

The process has evolved to increase thermal efficiency, decrease capital costs, and increase productivity. Schematics of alternative kiln configurations are provided in Exhibit 4-1. The following is a brief summary of the process evolution and potential for tire and TDF usage in each process:

- **Long Wet Kilns:** A long wet kiln system is the top schematic in Exhibit 4-1. Raw materials are ground and blended in a wet slurry to achieve uniformity. All drying and reactions take place in a rotary kiln up to 150 meters (500 feet) long. Long wet kilns are expensive to construct, operate, and maintain. Evaporating slurry water makes the operation extremely energy intensive. Whole tires can be introduced into the calcining zone of the kiln through a process called mid-kiln injection. A hole is cut into the kiln with internal baffles that prevent product escape. As the kiln rotates, a trap door is opened, one to three tires drop through the hole, and the door closes. An example of the sequence is shown in Exhibit 4-2. Shredded tires can also be blown into the firing end of kiln through a smaller pipe parallel to the main coal firing nozzle. Nominal 2.5-centimeter (1 inch) TDF is normally used. The TDF system must be carefully designed to minimize pipe size and additional air while conveying TDF deep into the kiln. This prevents reducing conditions in the product near the end of the kiln. Both of these technologies have been broadly applied and are considered reliable and proven.

- **Long Dry Kilns:** Long dry kilns are similar to wet systems, but raw materials are ground and blended dry to reduce energy requirements associated with evaporating water from slurry. This results in increased productivity and decreased energy consumption. The methods for using whole tires and TDF are the same as in wet kilns.

- **Preheater Kilns:** A preheater kiln system is also shown schematically in Exhibit 4-1. The raw mix is preheated more efficiently by contact with hot combustion gases in a series of vertically stacked cyclones, allowing use of a shorter kiln to decrease capital and operating costs. TDF can be introduced into the preheater tower. Tires are normally injected into the kiln feed end through an airlock system. This system is analogous to mid-kiln injection in wet and dry kilns because it is near the beginning of the calcining zone.

Exhibit 4-3. U.S. cement facilities using tires
Source: Portland Cement Association

- **Preheater-Precalciner Kilns:** These kilns are similar to preheater systems, but an additional stationary combustion chamber is added at the bottom of the preheater tower. This additional chamber initiates calcining before the kiln and further reducing kiln length. This system has two combustion zones, one at the kiln firing end and the other in the precalciner. The combined hot combustion gas streams pass up through the preheater tower. TDF can be added into the riser section that transports gases from the kiln. Whole tires can be introduced through air locks into the feed end of the kiln or into the riser duct of the precalciner.

The technology for introducing and using whole tires and TDF in virtually all types of cement kilns has been proven over many years of operation in many facilities. Cement kilns have provided a constructive and inexpensive use for stockpiled tires in the United States, Canada, and many other countries. In fact, cement kilns are already using tires removed from stockpiles in the border areas of Mexico during stockpile abatement. Cement kilns in the United States often charge less to accept tires than other tire processing facilities or landfill disposal sites.

Logistics

Kilns are geographically dispersed throughout the United States and Mexico, with concentrations near population centers that generate large quantities of waste tires. Exhibit 4-3 shows the distribution of cement facilities using tires in the United States. Additionally, cement facilities located throughout Mexico, are shown in Exhibit 4-4.

Kilns are near rapidly growing border areas and other major industrial centers that generate scrap tires. Proximity of kilns to tire generation enhances logistical viability by decreasing the transportation cost for scrap tires. Transportation costs for whole tires and processed products are critical factors in constructively using scrap tire materials, as discussed in Chapter 6.

Energy Intensity

Although cement manufacturers have taken significant steps to reduce energy consumption, fuel is generally the biggest single manufacturing cost. Kilns are inherently energy intensive, and each one can use 500,000 to 1.5 million tires per year per kiln. Based on the U.S. RMA's kilns statistics cited earlier, each kiln using tires in the United States consumed an average of about1 million tires in 2007. Tires can generally displace 10 to 25 percent of the total fuel

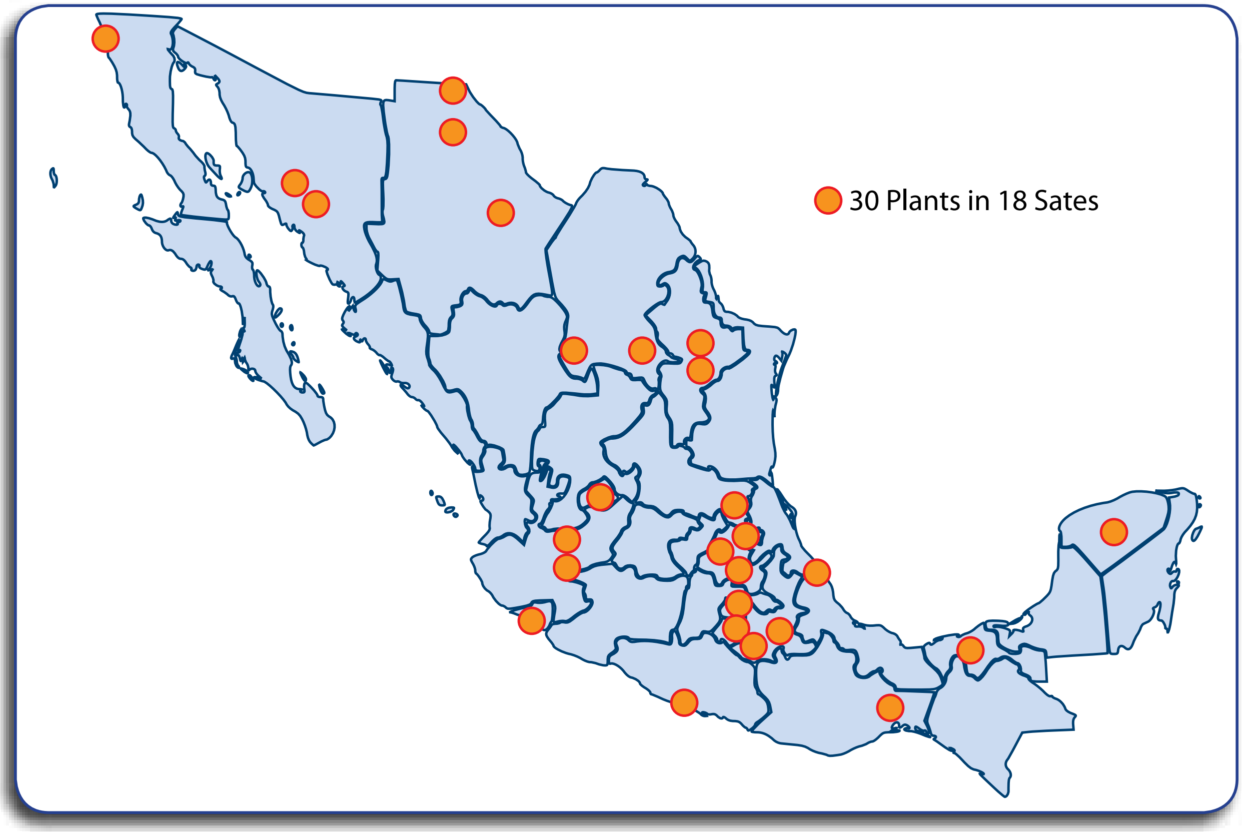

Exhibit 4-4. Mexico cement facilities

used in a kiln. Quantity is generally limited by raw material or product chemistry, combustion conditions within the process (predominantly air availability or sulfur build-up) or tire supply. In a competitive industry, the energy cost savings of TDF versus fossil fuels can provide a significant economic advantage.

TDF/Whole Tire Metering Systems

Cement kilns are large systems representing sinks of energy and materials that create operational inertia. Operators strive to maintain steady operating conditions and avoid variations that can impair the stability of the kiln. Since tires become integrated into the clinker product, the iron and other inorganic compounds in tires become part of the basic raw mix design and must be maintained on a constant basis to avoid a negative effect on the cement product. In fact, the steel in tires often displaces purchased iron, providing another economic savings, but it must be fed continuously.

Metering systems have been developed for whole and shredded tires to assure continuous, uniform supply to the kiln. Whole tire feeding systems can be as simple as manual operations that use a cable or hook conveyor to raise tires to the kiln floor, with people to weigh and insert tires into a simple airlock that feeds into preheater or precalciner kilns. These systems require limited capital investment, but need more labor. They can be useful during trial operations to define technical and environmental performance. An example of a simple metering system to introduce tires into a kiln is depicted in Exhibit 4-5.

Most companies in the United States attempt to minimize labor costs by making capital investments to replace human labor. These systems use trailer tippers to dump tires onto "singulators" that separate, convey, weigh, and insert tires into the kiln with minimal human oversight. Some manufacturers of this equipment have established reliability standards suitable for stable kiln operation, but the installed cost of these systems can be US$1 to $2 million per kiln. An example of an automated whole tire feed system is shown in Exhibit 4-6.

Mid-kiln injection requires a kiln portal and automated tire introduction to reduce personnel hazards, as shown in Exhibit 4-6.

TDF feed systems for dropping shreds into preheater-precalciner kilns generally involve less sophisticated handling systems. These can be as simple as a skid-mounted metering bin with transfer conveyors, weighing equipment, and an airlock. There are operational issues, but the equipment can be comparatively simple. Systems for blowing TDF into the firing end of long wet or dry kilns can be a low-capital cost option with a simple metering

Exhibit 4-5. Tire metering systems for kiln introduction
Photo courtesy of Terry Gray, TAG

bin, conveyor, TDF injection piping, and blower. However, critical design considerations include the need to (1) minimize additional blower air usage to control thermal efficiency impact; (2) assure deep penetration of TDF into the calcining area of the kiln; and (3) avoid nozzle failure by assuring continuous air flow through the nozzle.

When metering systems are explored, it is wise to obtain a list of previous customers, discuss performance with them, and view the systems in operation if possible. Use of whole tires or TDF can be reliable with proper selection, installation, and maintenance of equipment.

Environmental Performance of TDF Use by Kilns

The use of tires as TDF amounts to simply burning tires in a controlled environment and can be a viable option under the correct conditions, as demonstrated by diligent monitoring of existing operations. Air pollution control regulations vary from U.S. state to state; however, analysis of emissions data demonstrates that facilities remain within permissible limits. Compliance and performance monitoring are integral parts to any state pollution control program. The following factors encourage use of tires as a supplemental energy resource in cement kilns, but the application also must be environmentally acceptable and not pose unnecessary risks to health or the environment. Several additional factors that affect environmental performance warrant discussion:

- **Rigorous Combustion Conditions** — A unique combination of high temperature, long residence time, and turbulent air flow promotes complete combustion of organic compounds in cement kiln systems. Although tires are not hazardous wastes, the combustion conditions in cement kilns exceed the strict requirements for combustion of hazardous wastes in the United States. Combustion conditions for tires generally exceed 1,450°C (2,000°F) with air residence times in excess of 2 seconds.

- **SOx Control** — Limestone is commonly used to absorb SOx in air pollution control systems. It is also a major component in the cement raw mix. As a result, SOx in combustion gases is captured by the limestone in the raw mix as the gases pass through the kiln system, thereby providing an effective SOx control mechanism.

- **Ash Utilization** — Ash resulting from tire combustion becomes an integral component of the cement product, thereby eliminating the need to dispose of any ash from TDF combustion.

These factors support use of scrap tires as a supplemental fuel in kilns. However, historical performance is a critical consideration in evaluating environmental acceptability of this application. Extensive environmental data have been generated for a variety of kiln configurations and alternative fuel displacements (for example: scrap tires displacing coal as the fuel).

The following emissions test results are representative examples. Performance results for Ashgrove Cement's kiln in Durkee, Oregon, are provided in Table 4-3. Emissions of particulates, SOx, chlorides, and all heavy metals declined or remained constant. Total hydrocarbons increased about 10 percent, but polynuclear aromatic hydrocarbons (PAH) declined about 10 percent. This facility is fully permitted for waste tire usage in Oregon, one of the most environmentally sensitive states in the United States.

Trailer Dump

Singulator

Conveyors to Kiln

Airlock Introduction

Exhibit 4-6. Automated tire feed system components
Photos courtesy of CEMEX Corp

Several cement plants in the southwestern United States have undergone extensive testing. Emission results for California Portland Cement Company's Colton plant are summarized in Table 4-4. Some criteria pollutants decreased with use of tires, while others increased. For example, total particulates increased less than 10 percent, while non-methane hydrocarbons decreased about 18 percent. Recognized carcinogens such as benzene and toluene decreased. Total dioxins and furans (PCDD/PCDF materials) increased very little in quantity. Most polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) declined with tire usage while hydrochloric and hydrofluoric acids increased. Hexavalent chromium, barium, cadmium, lead, and nickel emissions declined while zinc and mercury increased. The emission testing results showed minor changes with a relatively balanced net impact.

California Portland engaged a consultant to conduct a comparative health risk assessment. The consultant used the latest versions of the Industrial Source Complex (ISC) dispersion model and U.S. Army Corps of Engineer's health effects model specified by the California EPA to place these relative impacts into a technical perspective. Based on this evaluation, the individual carcinogenic risk declined 47 percent with TDF usage while the noncarcinogenic health effects resulting from short-term exposure (acute hazard index) fell 94 percent and the noncarcinogenic health effects of continuous exposure (chronic health impact) decreased 72 percent. Exposure to toxins of any kind is a serious and potentially dangerous aspect of today's society; however, the exposure risk reductions demonstrated by California Portland Cement Company's kilns demonstrate the effectiveness of this technology as a method to use scrap tires and also shows that it compares favorably with use of other fuel sources.

Cement kilns have collectively used more waste tires than any other single application in the United States and this application is among the largest in Europe and Japan. Furthermore, kilns are an important component of waste tire management in most U.S. states. Some cement companies in Mexico have used, or are using, scrap tires as a supplemental energy resource. Cement companies in northern Mexico have cooperated with Mexican governmental departments to constructively use tires removed from border stockpiles under economic conditions that were attractive to both government and industry. The most critical factors controlling development of this application are a consistent tire supply and reasonable economics. Cement kilns provide an important opportunity for using waste tire resources constructively. Any state or local government that is not fully utilizing its waste tire resource may want to objectively evaluate the environmental and economic merits of using scrap tires as an energy resource in cement kilns.

PULP AND PAPER INDUSTRY

The pulp and paper industry combusts bark and waste wood in stoker-fired boilers to provide steam and power required for processing operations. Wood is combusted on moving grates that also transport residual ash from the boiler. Coal, oil, or gas can be fired into the boiler above the grate to enhance combustion and to maintain operating temperatures when the moisture content of waste wood is high from rain.

This application uses TDF obtained by processing scrap tires into uniform, flowable chips less than 5 centimeters by 5 centimeters (2 inches by 2 inches) in size. Bead wire is often removed magnetically to avoid fouling grates and ash handling systems. Representative 5-cm particulate TDF with bead wire removed is shown in the photo to the right.

TDF can be introduced separately or as an integral part of the wood mixture with relatively simple, inexpensive metering systems.

TDF can be placed on the feed wood conveyor belt to the boiler, as shown in the photograph to the right. TDF's high volatile carbon content enhances combustion of wood on the grate and improves fuel efficiency.

The environmental impact associated with use of TDF in this application depends on characteristics of the displaced fossil fuel and system environmental control equipment. The two common factors controlling environmental acceptability are sulfur oxides (SOx) and particulate (zinc oxide) emissions. SOx emissions may decrease if TDF displaces coal or oil with higher sulfur content. Alternatively, SOx can be controlled by the scrubbers present in some air filter systems, especially if the scrubbers operate at a neutral or basic pH. Particulate emissions can be controlled by electrostatic precipitators (ESPs) or baghouses. In general, many environmentally acceptable applications occur when TDF displaces coal in systems with baghouses or ESPs.

Based on data compiled by the U.S. Rubber Manufacturers Association in 2007, 32 U.S. paper mills used approximately 1.07 million tons of TDF, representing about 70 million scrap tires in compliance with applicable regulations. Other mills are also undertaking testing (Ref. 1). Usage has fluctuated, but the high cost of fossil fuels has led to a significant resurgence in TDF usage in paper mills as

TDF particulate with bead wire removed
Photo courtesy of Terry Gray, TAG

Metering system to introduce TDF into wood mixture before processing
Photo courtesy of Terry Gray, TAG

Table 4-3 Environmental Performance Data TDF Introduction Into Riser Section of Ashgrove Cement's Preheater Kiln

CRITERION	UNITS	BASELINE	9% to 10% TDF	PERMIT LIMIT
PARTICULATE	lbs/hr	5.27	4.83	18
SOx	lbs/hr	<1.5	<1.2	6.3
CHLORIDES	lbs/hr	0.268	0.197	NA
TOTAL HYDROCARBONS	lbs/hr	3	3.3	NA
POLYNUCLEAR AROMATICS (PNA)	lbs/hr	0.0058	0.0053	NA
HEAVY METALS				
Arsenic	micrograms	0.2	0.2	NA
Cadmium	micrograms	3	2	NA
Chromium	micrograms	30	ND	NA
Nickel	micrograms	30	ND	NA
Zinc	micrograms	35	35	NA
Copper	micrograms	37	13	NA
Lead	micrograms	ND	ND	NA
Iron	micrograms	400	200	NA
Barium	micrograms	ND	ND	NA
Vanadium	micrograms	ND	ND	NA

new mills have completed environmental testing and existing users have maximized consumption. This is especially true for facilities in the southwestern United States.

Table 4-5 provides environmental data associated with performance testing conducted at the Bucksport site. A baseline test was conducted using the normal mixture of gas, bark, coal, and sludge. TDF was then substituted for coal at levels representing 6.3 percent, 10.3 percent, and 14.5 percent of heat input. At the maximum TDF level, NOx, SOx, and total hydrocarbon emissions remained virtually unchanged while particulate matter increased 6 percent. Among the metals, beryllium and chromium decreased, lead remained below detection limits, and cadmium increased. Zinc increased significantly percentage-wise, but total quantities remained environmentally acceptable. Overall particulate emissions remained well within acceptable limits.

The International Paper facility in Bucksport, Maine, has been one of the largest users of TDF since 1990. Its boiler is capable of consuming up to 3.5 tons of TDF per hour (14.5 percent by heat input) to produce almost 225,000 kilograms (500,000 pounds) of steam per hour.

Performance data have also confirmed the environmental acceptability of TDF in similar paper mills and industrial boilers in 20 U.S. states. Several of these states (including Oregon, Washington, California, and Florida) are recognized for their high environmental standards and rigorous regulatory enforcement. However, these applications must be carefully screened to define facilities capable of using TDF within environmentally acceptable limits. Only a small percentage of paper manufacturing and industrial facilities in the United States have the required combination of system design, permitting

Conveyor belt to introduce wood and TDF into boiler system
Photo courtesy of Terry Gray, TAG

Table 4-4 Environmental Performance Data California Portland Cement Kiln (Expressed as Pounds/Hour)

CRITERION	EXPONENT	BASELINE	12%TDF
PARTICULATE		7.35	8.01
NOx (ppm)		208.80	104..2
CO (ppm)		104.20	159.30
VOLATILE ORGANIC COMPOUNDS			
Acetaldehyde		0.34	0.05
Benzene		2.65	2.29
Formaldehyde		0.88	0.11
Toluene		3.98	3.17
Dichloromethane	E-3	1.79	0.87
O-xylene	E-3	1.89	2.14
Trimethyl benzenes	E-3	1.56	3.99
METALS			
Antimony	E-4	2.32	<2.28
Arsenic	E-4	4.05	0.85
Barium	E-3	1.20	0.48
Cadmium	E-4	2.27	1.77
Chromium (Total)	E-4	3.44	3.94
Chromium (Hexavalent)	E-4	2.33	1.13
Copper	E-3	1.11	0.72
Lead	E-3	1.19	0.59
Manganese	E-3	1.96	2.06
Mercury	E-3	4.54	8.33
Nickel	E-4	5.81	3.00
Selenium	E-4	ND<1.97	ND<6.54
Silver	E-5	ND<3.94	<4.55
Thallium	E-5	<2.52	<2.47
Zinc	E-3	4.71	9.41
NON-METHANE HYDROCARBONS		18.16	14.81
PCDD/PCDF	E-6	1.58	1.93
2378 TCDD TOX EQUIV	E-8	1.05	1.68
PCBs	E-6	3.16	2.89
PAH	E-2	4.31	3.44
HCl		<0.017	0.43

conditions, and fuel usage conducive to appropriate TDF usage.

PUBLIC UTILITY BOILERS

During 2007, 38 electric power utility and industrial facilities were consuming the equivalent of 35 million tires (495,000 metric tons), according to the U.S. Rubber Manufacturers Association (Ref. 1). This industry segment continues to increase, with additional growth projected in the future.

TDF can be used efficiently only in specific types of utility boilers (primarily cyclone, fluidized-bed, and stoker-grate units) that offer adequate retention time for complete combustion of nominal 2.5 centimeter (1 inch) TDF that is sometimes referred to as “minus (finer than) 5 centimeter” (“minus 2 inch”) TDF. This

Table 4-5 Comparative Emissions for International Paper Mill Bucksport, Maine (Expressed as Pounds/Mbtu)

CRITERION	BASELINE	14.5% TDF (BY HEAT)	PERCENT CHANGE
NOx	0.274	0.273	0
SOx	0.508	0.51	0
PARTICULATES	0.053	0.056	6
TOTAL HYDROCARBONS	1.17 E-3	1.18 E-3	1
BERYLLIUM	1.06 E-6	0.73 E-6	-31
CADMIUM	0.60 E-6	0.78 E-6	30
CHROMIUM	12.1 E-6	6.36 E-6	-47
LEAD	<10 E-6	<10 E-6	0
ZINC	0.26 E-3	2.56 E-3	885

TDF material is the smallest that can generally be produced at costs competitive with coal and other fossil fuels. These public utility units consume large quantities of fuel, so small percentages of TDF (2 to 4 percent) can use up to 5 million tires per year at a single facility.

This market appears to represent less potential in Mexico because of prevalent use of residual oil for power generation. Most oil-fired combustion units do not need nor have the ash handling and combustion chambers required for use of solid fuels such as TDF. As a result, detailed discussion of this application does not appear to be useful for Mexico, with the possible exception of fluidized-bed boilers.

Circulating fluidized bed boilers represent one of the newer systems designed to minimize environmental impact from use of solid fossil fuels. High turbulence and uniform heat distribution allow fluidized beds to operate at lower temperatures to minimize NOx formation. Ammonia injection may also be used for supplemental NOx reduction. Limestone is commonly used as the circulating bed media, providing efficient SOx control through integral mixing with combustion gases. Sophisticated baghouses or electrostatic precipitators remove particulates. These systems represent environmentally viable candidates for use of nominal 2.5-centimeter (1-inch) TDF.

The Stockton Cogeneration facility in Stockton, California conducted extensive trials with financial assistance from the California Integrated Waste Management Board to define the emissions characteristics associated with use of up to 20 percent TDF (by heat). The results of this analysis are compared with the facility's existing permit limits in Table 4-6. All emissions were well within permit limits, with particulate and hydrocarbons at less than 25 percent of established limits.

Dedicated Tire Combustion Units

Tires have even been used as a primary fuel in dedicated, specially designed power boilers in California, Connecticut, and Illinois, using 5 to 10 million tires per year. Although these systems use large quantities of tires that must be available in a limited geographic area, they are still small by power generation standards. As a result, the capital costs per megawatt are higher than a nuclear power plant. Two of the facilities have failed economically and have resulted in major capital losses. The Connecticut facility is still operating, but it has an abundant tire supply in the highest population density area of the United States and comparatively high electricity pricing. These dedicated systems are unlikely to be economically viable in Mexico just as they are not viable in the majority of the United States.

COMBINED ENERGY/MATERIALS RECOVERY: PYROLYSIS/GASIFICATION

Pyrolysis is, by definition, thermal decomposition of organic compounds in an oxygen-limited environment. Promoters have called the pyrolysis processes thermal distillation, destructive distillation, and many other names to avoid identification with historical pyrolysis failures. Pyrolysis of waste tires typically generates gas, oil, and char products. The quantity and quality of each product depend on many process variables, including temperature, pressure, and residence time. Twenty to 35 percent of a tire's energy content is typically converted into a combustible gas that is used to fuel the pyrolysis process or is combusted in a flare before it is released. Thirty-five to 50 percent of the output from the process is transformed into an oil product that varies in quality from saleable fuel oil to lower-value oil blend stock. The residual solid product (referred to as char) constitutes 25 to 40

Table 4-6 Emissions From A Circulating Fluidized Bed Boiler Stockton Cogen (Stockton, California) (Expressed as pounds/hour)

CRITERION	20% TDF (BY HEAT)	LOWER PERMIT LIMIT
NOx	25.06	39.00
SOx	33.40	59.20
PARTICULATES	2.19	10.00
CO	20.90	22.90
TOTAL HYDROCARBONS	<0.38	1.88

percent of the output and contains a mixture of the following materials:

- Multiple types of carbon black used in various sections of a tire for strength, wear, or other critical performance properties.
- Titanium dioxide from white sidewalls and lettering.
- Zinc dispersed uniformly within tires as a vulcanization accelerator.
- Steel from bead and radial reinforcing wire.
- Other trace inorganic compounds present in tires.

Historical Experience

Pyrolysis is not a new process. It was developed in Europe more than 60 years ago to transform coal into gas for street lamps. Over the past 25 years, many processes, equipment, and operating variations have been applied to scrap tires. A U.S. Department of Energy publication titled "Scrap Tires: A Resource and Technology Evaluation of Tire Pyrolysis and Other Selected Alternate Technologies" identified 31 pyrolysis projects in 1983 that used fluidized beds, traveling grate chambers, rotary kilns, retorts, molten salt and hot oil baths, plasma arc units, and microwave chambers as reactors. Various operating conditions have been extensively explored to optimize production and the quality of product streams. In spite of this extensive developmental effort, no commercial-scale pyrolysis systems currently operate continuously in North America.

Extensive technical and economic resources (more than $350 million) have been invested in projects developed by major companies world wide in support of pyrolysis. In addition, many pilot or "demonstration" projects have been developed by smaller companies and entrepreneurs. One major project developed by Foster-Wheeler in England (called Tyrolysis) failed technically and economically after expenditures that exceeded $30 million.

Major reasons for failure of pyrolysis projects have included the following:

- **Operating Problems:** Using complex equipment at high temperatures with an abrasive feedstock such as scrap tires is generally maintenance-intensive. Downtime and maintenance expenses have often been underestimated in projections of total project costs.
- **Safety:** Operating in an oxygen-limited, high-temperature environment creates the possibility of fires or explosions if air enters the system accidentally. These accidents have destroyed or damaged numerous pyrolysis facilities, including complete destruction of one operation in Texas.
- **Feed Availability and Processing:** The quantity of tires required for economic feasibility can be more than are available within an economical delivery area at projected net tipping fees. In addition, capital and operating costs associated with shredding or feedstock preparation are often underestimated.
- **Product Quality:** It is difficult to optimize quality and yields of three inter-related product streams (gas, oil, and char) since conditions that favor one often have a negative impact on another. Because of the mixture of carbon blacks and other constituents, the char has historically been

The Stockton Cogeneration facility in Stockton, California, conducted extensive trials with financial assistance from the California Integrated Waste Management Board to define the emissions characteristics associated with use of up to 20 percent TDF (by heat). All emissions were well within permit limits, with particulate and hydrocarbons at less than 25 percent of established limits.

suitable only for low-value applications with limited market volumes, even when the char is further processed to control size uniformity and iron content.

- **Environmental Impact:** Tires contain about 1.8 percent sulfur and 1.2 to 1.5 percent zinc by weight. These inorganic materials are not destroyed or decomposed thermally, so they remain in one or more of the pyrolysis products as dictated by an elemental mass balance for specific operating conditions. In addition, partially decomposed hydrocarbons may not be fully removed from the exhaust gas stream by condensation or combustion. As a result, pyrolysis systems must include air pollution control systems to prevent discharges to the environment. Pyrolysis promoters often claim that their process has no emissions because all materials are captured as products. However, the gas product is generally combusted to fuel the process or flared on site because it cannot be transferred in normal gas transmission lines. In either case, combustion creates emissions that require controls to comply with clean air standards in the United States. In addition, the char may require disposal as a hazardous waste if it is not marketable. These practical realities should be reflected in capital and operating cost projections.
- **Economics:** The economic feasibility of pyrolysis depends on many operating factors. These factors include system reliability, capital and labor costs, process, feedstock preparation expense, environmental control requirements, and product revenue. Past operations have not been economically sustainable at reasonable tipping fees because they have not been able to develop high-value (about 3.5 pesos or $0.33 per kilogram [$0.15 per pound]) markets for all of the char generated. The materials recovery appeal and economic viability of this process depend totally on being able to sell the carbon black content of the char stream at a relatively high price. Unless this objective is achieved, pyrolysis simply becomes a capital-intensive process for conversion of a solid fuel into a low-grade liquid fuel.

Current Practice

Many companies are promoting pyrolysis systems in North America. None of these technologies has been practiced on a commercial scale for an adequate period of time to fully demonstrate long-term operating economics and char marketability. It would be even more difficult to achieve economic viability with the low tipping fees likely to be encountered in Mexico.

One variation of pyrolysis refines the oil stream into high-value specialty chemical products. The product gas from the reactor is cooled in a heat exchanger, thereby condensing a broad range of partially decomposed chemical compounds to form "oil" suitable for use primarily as a low-value blend stock. The high capital cost and sophisticated control of multiple condensers or fractionation equipment required to produce and refine multiple liquid products are economically questionable for these relatively small oil volumes. Refining operations require high volumes to be economically viable. The oil generated by a large pyrolysis system using 2 million tires per year would represent less than 1 percent of refinery throughput required to operate at minimum capacity.

Gasification Variation

A variation of pyrolysis allows some air to be present to facilitate partial combustion. This drives the gas, oil, and char into a low heat value gas that contains predominantly carbon monoxide with some hydrogen and low molecular weight hydrocarbons. This gas is then burned to generate steam or power by many alternative methods, many of which are not economically practical at the projected scale of operation or with the particulate and chemical contaminants present in the gas. Although this variation overcomes the issue of char marketability by driving the carbon to carbon monoxide, it does not overcome air emissions issues when the gas is combusted. This process is simply two-stage combustion and must account for air emissions and material balances, as with the combustion applications. There are no known commercial-scale tire gasification system units operating on a self-sustaining economic basis in North America as of November 2009.

Summary and Recommendations

Tire pyrolysis and gasification facilities have not been able to demonstrate and sustain economic viability historically because of technical failures or the inability to obtain contractual commitments for all char products. Many pyrolysis facilities have failed during the past 20 years, generally leaving a government liability for abatement of accumulated tires as well as remediation of residual oil and char contamination. Requiring financial assurance to cover alternative disposal costs for maximum stored quantities of tires and char can be one appropriate method of protecting public interests.

Investors should conduct thorough due diligence before they make substantial equity or debt commitments to this technology. Critical questions about product quality, markets, safety, maintenance expense, and economics must be answered before this technology can be considered a proven alternative for disposal of scrap tires.

SUMMARY

Scrap tires can be an environmentally compatible alternative energy resource when used in appropriate applications. Energy use is an important component of successful scrap tire management programs within the United States in allowing this resource to be used productively. The net result has been substantial conservation of non-renewable fossil fuels. When the demonstrated performance of tires as an energy resource is objectively evaluated, many jurisdictions have concluded that the environment is better served by recognizing the value of this resource rather than wasting it while waiting for ideal solutions. Good scrap tire management programs recognize the importance of diverse applications.

Ideally, a tire's polymerized rubber mixture would be perpetually reused. However, today's applications for recycled rubber consume less than 17 percent of the waste tires generated annually in the United States. These markets are growing slowly in spite of intense market development efforts, and even the most optimistic projections show less than 25 percent use in 5 years.

Other major applications for scrap tires must be embraced and developed to constructively use this resource, or it will be squandered through landfilling or become a stockpiled public liability that poses public health and environmental hazards. Since few consciously want to waste a valuable resource, other applications that are compatible with the environment should become the foundation of market development efforts. Avoiding unnecessary consumption of these limited natural resources through use of scrap tires as an alternative energy resource is a worthy objective if it can be done without a counter-balancing negative impact on the environment.

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CHAPTER 5

Tire Derived Aggregate and Whole Tires for Civil Engineering Applications

Tire derived aggregate (TDA) is an engineered product made by cutting scrap tires into 25- to 300-millimeter (mm) pieces. In the United States in 2004, 60 million tires were used as TDA (Ref. 37). TDA provides many solutions to geotechnical challenges since it is lightweight (50 pounds per cubic foot [pcf]; 0.8 macrograms per cubic meter [Mg/m^3; note that the capital M distinguishes the acronym from the commonly understood micrograms per cubic meter]), produces low lateral pressures on walls (as little as one-half that of soil), is a good thermal insulator (eight times better than soil), has high permeability (more than 1 centimeters per second [cm/s] dependent on TDA size), has good shear strength, and absorbs vibrations. When used in appropriate applications, TDA's special properties can greatly reduce construction costs. Moreover, each cubic meter of TDA fill contains the equivalent of 100 passenger car tires.

TDA has been economically used for a wide range of functions in the United States. For example, it has been used as lightweight fill for highway embankments in 13 states. In the State of Maine, TDA is routinely used to improve the stability of embankments constructed on weak, marine clay, resulting in an average annual consumption of about 1 million passenger car tires (Refs. 8, 19, 27, 28, 41, 46, 49). TDA and TDA soil mixtures have also been used as a replacement for conventional soil in embankment construction (Refs. 15, 16, 43). The low unit weight and resulting low earth pressure, combined with its high permeability, make TDA an attractive backfill for retaining walls, bridge abutments, and sheet-pile walls (Refs. 19, 28, 45, 46). TDA has also been used as compressible layers behind integral abutment and rigid frame bridges (Refs. 27, 38). In this regard, Maine, Louisiana, Pennsylvania, and California have used TDA in retaining wall projects. In cold climates, TDA has been used to limit the depth of frost penetration and to provide drainage during the spring thaw (Refs. 20, 32). Furthermore, the permeability of TDA has led to significant use as drainage layers in landfills (Ref. 30), septic system drain fields, and highway edge drains (Ref. 32). Recent research has shown that a TDA layer beneath the stone ballast of rail lines reduces off-site vibrations that can affect adjoining residences and businesses (Ref. 51). This new technology was used on a light-rail commuter transit line recently completed in San Jose, California. Finally, a promising new idea for using TDA as backfill for bridge abutments to reduce earthquake loading was investigated by the University of California at Davis (Ref. 29).

The economics of using TDA for civil engineering applications depend on the local costs to produce TDA, as discussed in Chapter 6, and the local costs for competing alternative construction materials. TDA is generally cost competitive for projects that require use of lightweight fill material for embankment construction. Moreover, use of TDA in drainage applications is cost effective in areas where there is a limited supply of conventional drainage aggregate. TDA is not, however, a generally cost-effective substitute for conventional earth fill.

Guidelines and construction specifications are available to help engineers take advantage of the special engineering properties of TDA. Most important of these is ASTM International Standard D6270-98 (Ref. 3), Standard Practice for Civil Engineering Applications of Scrap Tires (*www.astm.org/Standards/D6270.htm*). This document lists the typical geotechnical properties of TDA, applicable test methods, and construction guidelines. Several studies have also shown that TDA has negligible impact on groundwater (see for example Refs 4, 5, 9, 10, 15, 16, 21, 22, 40). A statistical analysis of the effect of TDA on groundwater is presented in Humphrey and Swett (Ref. 26).

Use of TDA as *drainage aggregate* and *lightweight fill* will be presented in the following sections. The level of sophistication in specific applications varies. Some applications are for large civil engineering projects that must be designed by qualified engineering professionals. Other applications are small scale and can be implemented by municipal officials such as public works directors. Recommended materials specifications are presented in Appendix A. TDA with a maximum size of about 75 mm (3 inches) is referred to as Type A TDA, while TDA with a maximum size of about 300 mm (12 inches) is referred to as Type B TDA. Type A TDA is appropriate for a range of drainage applications in layers up to 1 m (3.3 feet) thick. Type B TDA is used for lightweight fill applications in layers up to 3 m (10 feet) thick. Three TDA projects in 1995 and 1996 underwent internal heating reactions, which prompted development of engineering guidelines to limit internal heating of TDA fills. The guidelines, as well as discussion of possible causes, are included as Appendix B. Experience on full-scale projects has shown that these guidelines are effective (Ref. 18). The engineering properties of TDA are discussed in detail in Appendix C. Use of whole tires for civil engineering applications is also discussed in this chapter.

TDA AS DRAINAGE AGGREGATE

TDA can be used as a substitute for conventional drainage aggregate for a wide range of applications. This material is advantageous when conventional aggregate is more expensive or is unavailable. Potential drainage applications include:

- Drainage layers within landfill leachate collection and removal systems.
- Permeable aggregate for landfill gas collection layers and trenches.
- Free draining aggregate for edge drains for roadways.
- Permeable backfill for exterior walls below the ground surface.
- Septic system drain fields.

TDA with a maximum size of 75 mm (3 inches) is appropriate for most of these applications.

The most important engineering property for drainage applications is permeability, also known as hydraulic conductivity, a measure of the capacity of a material to transmit a fluid. Permeability is related to void ratio, which is a measure of the void space between the aggregate particles. The fluid flows through the void space. For both of these properties, the void ratio, and in turn the permeability decreases as the vertical stress increases. These properties will be discussed in detail in Appendix C. However, key results are reviewed in this section. As shown in Exhibit 5-1, the void ratio of compacted TDA is between 0.8 and 0.9. However, the void ratio is less than 0.1 at stresses above about 400 kiloPascals (kPa) (9,000 pounds per square foot [psf]). This ratio stress corresponds to about 23 m (75 feet) of overlying soil fill. At void ratios this low, even a small amount of clogging could result in a significant decrease in permeability. Therefore, it would be reasonable to set 0.2 as a lower limit for void ratio for many applications, which corresponds to the void ratio of well-graded clean sand. The void ratio restriction would limit use of TDA in drainage applications to vertical stresses less than about 240 kPa (5,000 psf). Stresses this high could be encountered for some applications where TDA is used as a drainage layer in a landfill leachate collection and removal system. However, stresses in other landfill and roadway applications will likely be less than this limiting value.

The permeability of TDA decreases as the void ratio decreases, as shown in Exhibit 5-2. The permeability will be greater than 1 cm/s at void ratios typical of highway applications (greater than 0.4). At a void ratio of 0.2, the permeability is about 0.25 cm/s, which is adequate for most drainage applications. For comparison, the permeability of well-graded clean sand is typically 1 x 10^{-2} cm/s (Ref. 14), so TDA is more permeable than many readily available granular materials.

The use of TDA in specific drainage applications will be discussed in the following subsections.

Landfill Leachate Collection and Removal Systems

New municipal solid waste landfills (MSWLF) are generally designed with a composite liner to limit outward migration of leachate, and a leachate collection and removal system (LCRS) that is designed to maintain less than 300 mm of leachate over the liner (see Subtitle D landfill regulations at Title 40 Code of Federal Regulations [CFR] Part 258.40(a)). Approximately half of the U.S. states require that aggregate used for a LCRS have a permeability greater than either 1 x 10^{-2} cm/s or 1 x 10^{-3} cm/s (Ref. 31). In addition, the LCRS should be designed to function without clogging throughout the life of the landfill and the post-closure maintenance period (see, for example, Title 27 of the California Code of Regulations). Moreover, the aggregate must be stable on side slopes. Finally, the aggregate should not damage the underlying composite liner during construction and operation. TDA used as a component in an LCRS should have a maximum size of 75 mm (3 inches) and meet the requirements for Type A TDA given in Appendix A. Textbooks such as "Geotechnical Aspects of Landfill Design and

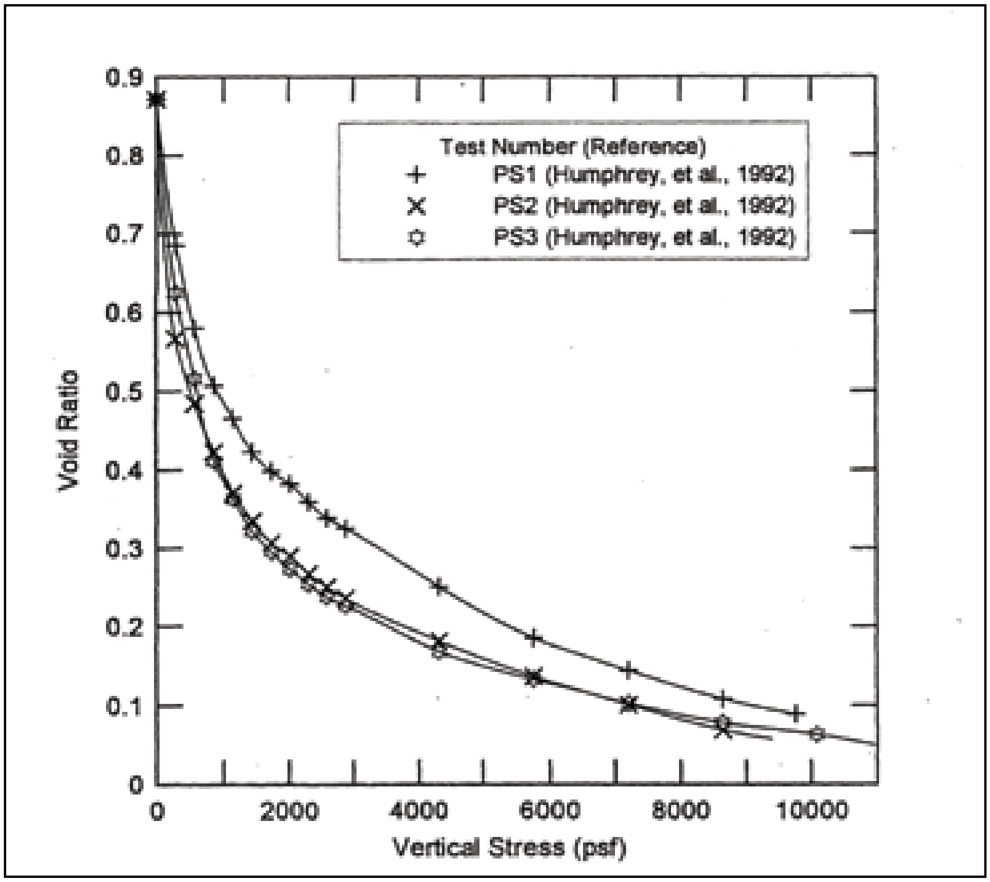


Exhibit 5-1. Void ratio vs. vertical stress for Type A TDA

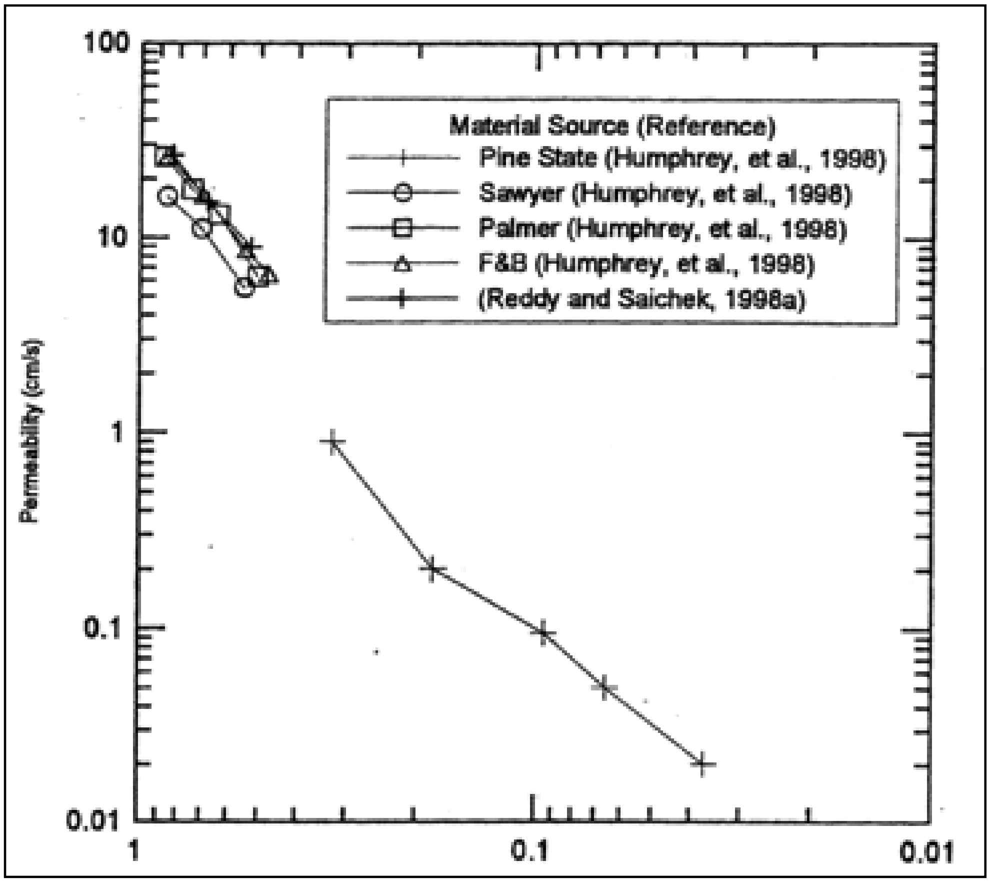


Exhibit 5-2. Permeability vs. void ratio for Type A TDA

Construction" by X. Qian, R.M. Koerner, and D.H. Gray, Prentice Hall, 2002, and applicable government regulations should be consulted for general principals and specific requirements of LCRS design. In the following section, only those aspects that are specific to the use of TDA are discussed.

The permeability of TDA is adequate for many LCRS applications and will generally exceed 1 x 10^{-2} cm/s. However, the TDA layer is compressed by the weight of the overlying waste and its void ratio is decreased. At high stresses, the void ratio can decrease to less than 0.1, as shown in Exhibit 5-1. The TDA would be susceptible to clogging at void ratios this low. A minimum void ratio of 0.2 is therefore recommended. This ratio would limit the vertical stress caused by the overlying material to about 240 kPa (5,000 psf). An in-place unit weight of municipal solid waste (MSW), including a reasonable amount of daily soil cover, would typically be 0.8 to 1.1 Mg/m3 (50 to 70 pcf) (Ref. 36). This weight will limit the thickness of overlying waste to about 20 m to 30 m (70 feet to 100 feet).

The compressibility of the TDA must be considered in selecting the TDA layer thickness. In general, the layer must be overbuilt to compensate for compression under the weight of the overlying MSW, so that the thickness of the layer will meet design requirements after compression. Table 5-1 should be used for guidance in determining the amount of overbuild.

Table 5-1. Compressibility of Type A TDA.

Vertical stress kPa (psf)	Vertical compression (%)
69 (1440)	19-33
138 (2880)	25-37
207 (4320)	29-42
276 (5760)	33-44
345 (7200)	36-46
414 (8640)	39-48
483 (10,080)	40-50

Table adapted from GeoSyntec (1998b); source of data Manion and Humphrey (1992) and Humphrey and others (1993)

In addition, steel bead wire protruding from the cut edges of TDA can puncture the underlying geomembrane. Bead wires are the stiff bundle located where the tire contacts the rim. The possibility that bead wires could puncture geomembrane was investigated in a field trial conducted by the California Department of Resources Recycling and Recovery (CalRecycle; Refs. 11, 12). Test sections were constructed with TDA placed directly on geomembrane, separated from the geomembrane with geotextile with weights up to 1,620 grams per square meter (g/m^2) (48 ounces per cubic yard [oz/yd^2]), and separated from the geomembrane with drainage geocomposite. The installation was tracked with 100 passes of a Caterpillar D-7G bulldozer with an operating weight of approximately 20,400 kg (45,000 pounds). In all cases, the exposed steel bead wire punctured the underlying geomembrane even when protected by geotextile or geocomposite. An example puncture is shown in Exhibit 5-3. However, a test section with 300 mm (12 inches) of gravel as a separator between the TDA and the geomembrane showed no signs of puncture (Refs. 11, 12). Thus, the TDA for liner systems that contain a geomembrane should be separated from the geomembrane by at least 300 mm (12 inches) of conventional drainage aggregate. Alternatively, the tire can be debeaded before it is shredded in regions with low labor costs, and the restrictions discussed in the next paragraph can be followed.

The field trial conducted by CalRecycle (Refs. 11, 12) showed that finer belt wire that is located in the tread and sidewall portions of the tires does not puncture the geomembrane. However, belt wire can create some minor indentations, scratches, and dents in direct contact with the geomembrane. Although not confirmed by testing, it is thought that this minor damage may reduce the tensile strength of the geomembrane (Refs. 11, 12). The TDA may be placed in direct contact with the geomembrane if the bead wire has been completely removed in flat areas where the tensile strength of the geomembrane is of little

Exhibit 5-3. Example of steel bead wire puncturing geomembrane (Ref. 12)

importance. The geomembrane should be protected with geotextile (270 g/m^2 (8 oz/yd^2) or heavier) on side slopes where the tensile strengths of the geomembrane is important.

A typical design that incorporates TDA as a component in the LCRS would be 300 mm (12 inches) of conventional drainage aggregate overlain by 300 mm to 450 mm (12 to 18 inches) of Type A TDA. The compressed thickness of the TDA layer would generally be 300 mm (12 inches) or greater. The TDA would typically be spread in a single lift (layer) with a low-ground contact pressure bulldozer. The layer should be compacted by four passes of the bulldozer. A geotextile should be used as a separator to minimize infiltration of fines for TDA placed directly on a compacted low-permeability soil layer. A 1-hectare TDA drainage layer that is 450 mm (18 inches) thick would require the equivalent of 300,000 passenger car tires.

Landfill Gas Collection Systems

Landfill gas (LFG) collection systems are used to collect landfill gases and convey them directly to the atmosphere or to a central location where they are burned. LFG is collected by one or more of the following features: horizontal blankets of permeable aggregate placed beneath the intermediate or final cover; horizontal trenches of permeable aggregate located within the landfill; or vertical wells filled with permeable aggregate. A perforated pipe may be used in conjunction with permeable aggregate to increase the extraction capacity. LFG collection systems may be passive, so that the permeable aggregate simply provides a pathway to convey the LFG to the atmosphere; or active, so that a vacuum is used to extract the LFG from the landfill. The high permeability of TDA allows it to be substituted for conventional aggregate in many LFG collection applications. The general principles of LFG collection system design are presented in texts such as Qian and others (Ref. 36) and applicable governmental regulations.

TDA Gas Collection Blanket

Several factors must be considered when TDA is used as a gas extraction blanket placed beneath a final cover system. For most applications, the blanket will be covered by less than 1 m (3.3 feet) of earthen materials. Thus, the vertical stress on the blanket will generally be less than 20 kPa (400 psf). Exhibit 5-1 indicates that the void ratio at this stress would likely be greater than 0.6. Exhibit 5-2 indicates that the permeability would likely be greater than 1 cm/s. These values are comparable to conventional aggregate used in this application. The compression of the TDA under the weight of the overlying cover also must be considered. Although the compression will be small at low stresses, it is recommended that the as-placed thickness of the layer be increased by 10 percent to compensate for the compression that will occur under the weight of the overlying cover. A geotextile should be used to separate the TDA gas collection layer from an overlying earth cover. Type A TDA is appropriate for this application. The material specifications for Type A TDA are listed in Appendix A.

The TDA layer should be spread on a properly graded and compacted foundation layer constructed of soil. The TDA can be spread as a single lift. It should be compacted by six passes of a vibratory smooth-drum roller with a minimum operating weight of 9.8 metric tons (10 U.S. tons).

The compressibility of the TDA gas collection layer presents several issues for placement of the overlying cover system. A field trial conducted for CalRecycle (Refs. 11, 13) found that construction of a compacted clay liner (CCL) base consisting of 300 mm (12 inches) of compacted soil underlain by 300 mm of TDA resulted in a CCL that developed excessive cracks. Increasing the compacted soil base to 450 mm (18 inches) provided an adequate surface for construction of the CCL with a hydraulic conductivity of 1 x 10^{-6} cm/s or less (Ref. 13). Thus, a minimum thickness of 450 mm (18 inches) of compacted soil must be spread on the TDA gas collection layer to form a soil base for construction of the overlying CCL. A geotextile should be installed as a separator between the TDA gas collection layer and the overlying soil base layer.

Some landfill designs call for a geomembrane as the barrier layer in a landfill cap system. The geomembrane cannot be placed directly on the TDA gas collection layer because of the risk of puncture from steel belt wire exposed at the cut edge of the tire chips. Moreover, the compressibility of the TDA would make it difficult to construct seams between adjoining geomembrane sheets and to maintain the integrity of the seams during subsequent construction operations. For these reasons, a 300-mm (1-foot)-thick compacted soil base layer should be spread on the TDA before the geomembrane is put in place. A geotextile should be placed as a separator between the TDA gas collection layer and the overlying soil base layer.

TDA Gas Collection Trench
TDA can be used in place of conventional aggregate for many LFG collection trench applications. Gas collection trenches can have several configurations. They include trenches at periodic intervals within the waste; trenches excavated through intermediate soil cover layers; and gas removal sumps placed at the bottom of landfills. For these configurations, a perforated pipe is generally surrounded by a permeable aggregate. The aggregate must be permeable enough to convey LFG to the extraction pipe and provide protection for the pipe itself. LFG collection trenches may need to operate for only a finite period of time, and a geotextile separation layer is generally not used. In cases where the trench is expected to be operational under waste thicknesses greater than 30 m (100 feet), consideration should be given to the adequacy of the compressed void ratio and permeability. The dimensions of the LFG collection trench and perforated pipe should be set based on the expected rate of gas generation and engineering principles such as discussed by Qian and others (Ref. 36). There are many successful applications in the United States where TDA has been used as backfill for LFG collection trenches.

TDA Gas Extraction Wells
The initial step in construction of a vertical gas extraction well is typically to drill a hole into the landfill using a 0.6- to 0.9-m (2- to 3-foot)-diameter bucket auger. A schedule 80 perforated polyvinyl chloride (PVC) pipe with a diameter between 100 and 150 mm (4 to 6 inches) is placed in the center of the hole and the annular space is backfilled with 25- to 50-mm (1- to 2-inch)-diameter washed stone (Ref. 36). It is possible that Type A TDA could be substituted for the washed stone.

There will be minimal compaction of the TDA for this application. Therefore, it is expected that the in-place unit weight at the time of placement would range between values for loose, uncompacted TDA and compacted TDA. The uncompacted unit weight of Type A TDA typically ranges from about 0.4 to 0.5 Mg/m^3 (25 to 31 pcf). However, uncompacted unit weights as low as 0.34 Mg/m^3 (21 pcf) have been reported for shreds with an excessive amount of exposed steel belts. The compacted unit weight of Type A TDA is typically about 0.64 Mg/m^3 (40 pcf) (Refs. 2, 24, 33). It is expected for the proposed application that the in-place unit weight when it is placed will range between 0.4 and 0.64 Mg/m^3 (25 and 40 pcf). The self-weight of the TDA will be largely supported by the side of the borehole, so little compression of the TDA as a result of the self-weight and the weight of overlying material is expected. However, it is expected that the TDA will compress over time by the same amount as the adjoining waste. Assuming that the waste compresses 20 percent over the active life of the collection well, the final unit weight of the TDA is expected to range between 0.5 and 0.8 Mg/m^3 (31 and 50 pcf). This amount of compaction corresponds to void ratios between 0.50 and 1.4. The void ratio of washed stone would typically be about 0.43. Thus, the in-place void ratio of TDA is expected to be larger than for 25- to 50-mm (1- to 2-inch)-diameter washed stone.

The permeability of TDA with a void ratio of 0.50 would be greater than about 9 cm/s based on Exhibit 5-2. Permeability data for TDA with a void ratio of 1.4 are unavailable, but permeability is expected to be high. Overall, the void ratio and permeability data indicate the performance of that Type A TDA and 25- to 50-mm (1- to 2-inch)-diameter washed stone will be similar to backfill for vertical gas collection wells. There are currently no known projects in the United States where TDA was used as the permeable aggregate placed in vertical boreholes.

An alternative installation procedure was used for TDA as the backfill for vertical gas collection wells in the Yolo County Central Landfill (YCCL) in California. The wells in this landfill were installed as the waste was placed. The general construction procedure was to use wire mesh to form a 1.2-m (4-foot)-diameter cylinder where the TDA was placed. Perforated pipe was located in the center of the TDA. The level of the TDA was always kept above the adjoining waste during construction. The TDA was termed "rough shreds," and its maximum size was greater than 300 mm (12 inches). These wells have been in successful operation for many years.

Drainage Applications for Major Highways

Excess water in the base of paved roads can significantly decrease their service life. TDA can be used in two ways to help remove water from the roadway cross section. The first is a permeable drainage layer beneath the conventional aggregate base course. The TDA must be covered by between 1 and 1.5 m (3.28 and 5 feet) of conventional aggregate to minimize the influence of the TDA's compressibility on the performance of the overlying pavement for paved roads with heavy traffic volume. Thus, the TDA for this application must be located relatively deep in the pavement cross section.

The second application using TDA is as a replacement for conventional drainage applications in highway edge drains. These drains are located beyond the edge of the traveled way, so the restriction on the thickness of overlying cover does not apply. The conventional aggregate base course should drain into the edge drain. Use of edge drains is particularly appropriate in cut sections where it is not possible to obtain gravity drainage to an adjoining ditch and in locations where the groundwater table is high, as well as in urban locations where construction of perimeter ditches is impractical.

Drainage layers beneath paved roads should consist of 300 mm (12 inches) of Type A TDA (75-mm [3-inch] maximum size). It should be placed as a single lift and compacted with six passes of a vibratory smooth drum roller, smooth drum static roller, sheep or tamping foot roller, or bulldozer with conventional width tracks. The minimum operating weight should be 9.8 metric tons (10 U.S. tons) for each type of equipment. To minimize infiltration of surrounding soil, the TDA should be encapsulated with permeable geotextile meeting the requirements of American Association of State Highway Transportation Officials (AASHTO) M288, Class 2. Additional information on AASHTO requirements is available as part of the compilation, "Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 30th Edition and AASHTO Provisional Standards, 2010 Edition" available at *https://bookstore.transportation.org/item_details.aspx?ID=1597*.

TDA for edge drains should be Type A with a maximum size of 75 mm (3 inches). It should be placed in 300-mm (12-inch) lifts, and each lift should be compacted with six passes of a walk-behind roller with a minimum operating weight of 1 metric ton (1 U.S. ton). To minimize infiltration into surrounding soil, the TDA should be encapsulated with permeable geotextile meeting the requirements of AASHTO M288, Class 2. The slope at the bottom of the trench should be 1 percent or greater toward a drainage outlet. The drainage capacity of a trench with this slope and a cross-sectional area of 1square meter (m2) will be in excess of 1 cubic meter per second (m3/sec). If this capacity is inadequate, then a perforated pipe may be incorporated into the base of the edge drain.

Drainage Applications for Local Roads

The general principles for using TDA for drainage applications for local roads are similar to those for major highways. However, local roads will have lower traffic volumes and in some cases may be unpaved. For paved roads with low traffic volume, 0.75 m (2.5 feet) of aggregate base course should be placed over TDA drainage layers. Moreover, the TDA for paved roads should be separated from the surrounding soil by geotextile that meets the requirements of AASHTO M288, Class 2. For unpaved roads with low traffic volume, 0.6 m (2 feet) of aggregate base should be spread over TDA drainage layers; the use of a geotextile separation layer is optional.

The use of TDA as permeable aggregate for edge drains for local roads is the same as for major highways, with the exception that use of a geotextile separation layer is optional for unpaved roads.

Drainage Applications for Small-Scale Municipal Construction

Permeable aggregate is needed in several applications for small-scale municipal construction. In some cases, Type A TDA can be substituted for conventional drainage aggregate. This substitution is advantageous when conventional aggregate is more expensive or is unavailable. Possible applications include:

- Backfill for walls less than 1 m (3.3 feet) high.
- Backfill around the foundation walls for buildings.
- TDA-filled trenches in lieu of small-diameter culverts to convey small quantities of storm runoff to convenient discharge locations.

The TDA for these applications can be placed by hand or by available construction equipment. The TDA should be placed in 300-mm (1-foot) lifts and compacted by a hand tamper. Use of a geotextile separator between the TDA and the adjoining soil is optional, but it would prolong the service life of the installation by limiting inward migration of soil, which would reduce the permeability of the TDA. The TDA should be covered by a minimum of 300 mm (12 inches) of soil for areas that will be covered by vegetation, 450 to 600 mm (18 to 24 inches) of base course aggregate for unpaved areas that will be subjected to low traffic volumes, and 600 to 750 mm (24 to 30 inches) of base course aggregate for paved areas that will be subjected to low traffic volumes.

TDA should not be used as fill beneath buildings since the compressibility of the TDA could cause structural damage to the overlying building. TDA with exposed steel bead or belt wire should never be left exposed at the ground surface because of the risk of cuts and punctures to humans and other animals.

Drainage Applications for Septic System Drain Fields

Given the permeable nature of TDA, it has become an attractive option to replace traditional stone backfill material within septic system drain fields. Several U.S. states have begun allowing its use for new construction of these drainage fields. It has been found to reduce the expense and labor needed to construct traditional systems, and TDA is capable of holding more water than is stone. Transportation of the material is also more efficient and easier given its light weight. TDA can be a beneficial option in areas with abundant scrap tire supplies and where stone is not readily available and is expensive to transport.

TDA AS LIGHTWEIGHT FILL

The low in-place unit weight and relatively low cost make TDA an attractive lightweight fill for embankments constructed on weak ground, landslide stabilization, and retaining wall backfill. Proper use of TDA as lightweight fill can result in an increased factor of safety against a global slope stability failure, reduced-long term settlement, and lower construction costs. Since each cubic meter of TDA fill contains the equivalent of 100 passenger car tires, even relatively small projects can consume large quantities of tires. For example, 1.2 million passenger car tires (PTE; passenger tire equivalents) were used for the approach fills for a highway overpass in Portland, Maine. Design considerations for use of TDA as lightweight fill are provided in the following section. Then, specific applications of TDA as lightweight fill are discussed. As previously mentioned, the internal heating of TDA has the potential to cause a reaction; however, the potential is greatly decreased if the engineering specifications discussed in Appendix B are followed. Any project using TDA as lightweight fill must be designed by a geotechnical engineer who is well versed in soil properties, stability analysis techniques, and settlement calculation methods.

Design Considerations for use of TDA as Lightweight Fill

There are several special considerations for design of projects using TDA as lightweight fill. These considerations include estimating the final in-place unit weight of the TDA, calculating the overbuild of the TDA layer needed to compensate for compression under the weight of overlying materials, estimating the required thickness of overlying soil cover, and following guidelines to limit internal heating. These considerations are discussed in the following subsections. A detailed discussion of the engineering properties of TDA is given in Appendix C. Many of these properties will be necessary for the geotechnical design of TDA lightweight fills. A procedure for estimating the final in-place unit weight of TDA and overbuild is given in Appendix D.

Thickness of Overlying Soil Cover

Sufficient soil cover must be placed over the compressible TDA layer to preserve the durability of the overlying pavement, as investigated by Nickels (Ref. 34) and Humphrey and Nickels (Ref. 25). Cover thickness is defined as the combined thickness of base course and soil measured from the bottom of the asphaltic concrete pavement to the top of the TDA layer. Computer modeling showed that the tensile strain at the base of asphaltic concrete pavement with 760 mm (30 inches) of soil cover over the TDA layer was the same as a control section underlain by conventional aggregate and soil. They also predicted that the tensile would be similar for as little as 457 mm (18 inches) of soil cover. Soil cover thicknesses between 0.5 and 1.2 m (20 and 47 inches) are recommended, depending on the traffic loading. The lower end of this range may be acceptable for applications with low truck traffic, such as parking lots and rural roads. However, the surface deflections under heavy vehicles immediately after the soil cover is placed will be noticeable, although it will decrease with additional traffic.

Guidelines to Limit Heating

Three thick TDA fills (greater than 7.9 m [26 feet] thick) have undergone a self-heating reaction. Two of these projects were located in Washington State, and one was in Colorado. These projects were constructed in 1995, and each experienced a serious self-heating reaction within 6 months after they had been completed (Ref. 17). The lessons learned from these projects were condensed into design guidelines developed by the Ad Hoc Civil Engineering Committee (Ref. 1), a partnership of government and industry that deals with reuse of scrap tires for civil engineering. The overall philosophy behind development of the guidelines was to minimize the presence of factors that could contribute to self-heating. The guidelines were subsequently published by ASTM International (then the American Society for Testing and Materials, Ref. 3) and distributed by the Federal Highway Administration. The guidelines are given in Appendix B.

Highway Embankments Constructed on Weak Ground

The purpose of using TDA as lightweight fill for highway embankments constructed on weak, compressible soil is to increase global stability and reduce long-term settlement. There is no universal design for this application. However, most designs share the following features:

- Ingress of air and water is limited by a low-permeability soil cover on the sides and top of the TDA zone. The low-permeability soil cover should be inorganic soil with a minimum of 30 percent passing the No. 200 (0.075 mm) sieve. The thickness of the low-permeability soil layer typically ranges between 0.6 and 2 m (2 and 6 feet).

- Geotextile that meets the requirements of AASTHO M288, Class 2, is used to separate the TDA from the adjoining soil.

- The TDA is placed in 300-mm (12 inch)-thick lifts, and each lift is compacted by six passes of compaction equipment with a minimum operating weight of 9.8 metric tons (10 U.S. tons). The compaction equipment may be a smooth drum vibratory roller, a tamping foot roller, or a bulldozer with conventional width tracks.

- The projects use Type B TDA (see Appendix B for material specifications).

- The projects fully comply with the guidelines to limit heating (Appendix B).

A typical cross section of a lightweight embankment fill project is given in Exhibit 5-6. The use of TDA for this application is illustrated further by two case histories given in Appendix E.

Fill Construction in the Mexico City Basin

Many of the populated areas of Mexico are underlain by volcanic lacustrine clay, including Mexico City (Ref. 52). The clay has a very porous structure because of the high content of microfossils and diatoms (Ref. 7). Engineering characteristics of this soil include a high liquid limit, water content in excess of the liquid limit, a high void ratio (up to e = 14), expansion when wetted, sensitivity to remolding, low shear strength, high compressibility, and high

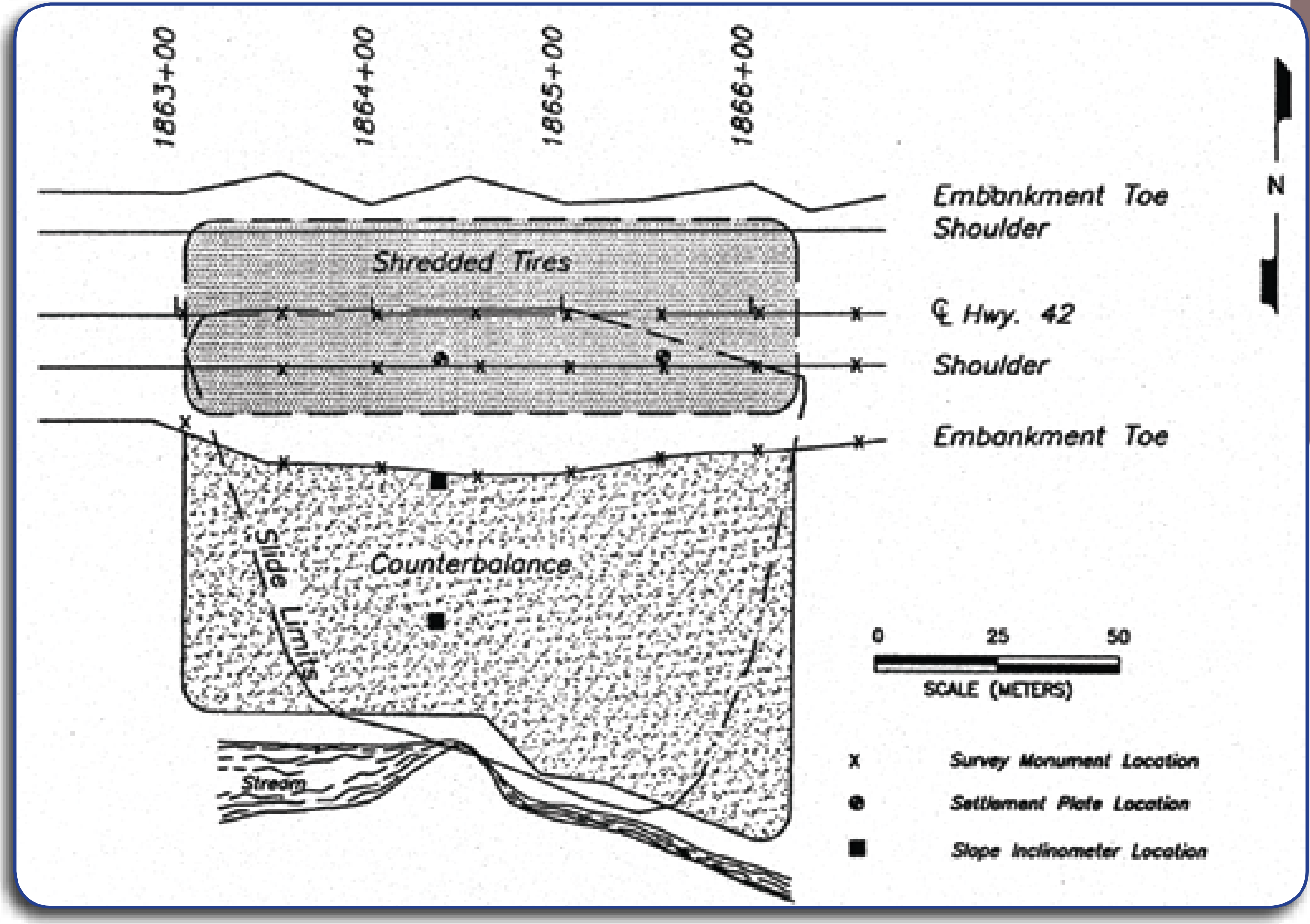


Exhibit 5-4. Plan view of Oregon tire shred field trial (Ref. 47)

secondary compression (Refs. 7, 52). For instance, the thickness of the underlying volcanic lacustrine clay near the Palace of Fine Arts in Mexico City is 180 m (600 feet) (Ref. 48). One technique to overcome the challenges presented by this highly compressible soil would be to use TDA as lightweight fill to construct embankments and low-unit-weight backfill for walls. It is recommended that opportunities to use TDA in areas of the country underlain by volcanic lacustrine clay be vigorously pursued.

Landslide Stabilization

Landslides can have a significant impact on roads and other infrastructure. In cases where the head of a slide intersects a road, it may be possible to use TDA as lightweight fill to help stabilize the slide. The design principle is to excavate the soil off of the top of the slide and replace it with lightweight TDA fill to reduce the force driving the slide. In some cases, use of TDA as lightweight fill is combined with other techniques, including constructing a berm of soil or rock at the toe of the slide to increase the resisting force, changing the geometry of the slope to improve the stability, or adding drainage features to remove excess water from the base of the sliding mass. The use of TDA for landslide stabilization will be illustrated using a case history.

The case history is located on U.S. Route 42 near Roseburg, Oregon (Ref. 47). As part of a project to improve the highway's alignment, an embankment was raised and widened, which reactivated an old slide. The head of the slide was stabilized by using TDA as lightweight fill to reduce the driving force, placing a counterbalancing fill at the toe of the slide to increase the resisting force, and adding a drainage blanket to remove excess water. The project is shown in plan in Exhibit 5-4 and in cross section in Exhibit 5-5. The earthwork was done in 1990, and final paving was completed in 1991.

The specifications for this early project called for TDA with 80 percent passing the 200 mm (8-inch) size and 50 percent larger than the 100-mm (4-inch) size; the maximum size measured in any direction was 610 mm (24 inches). The specification for metal fragments was as follows: "All metal fragments were to be firmly attached and 98 percent embedded in the tire sections from which they are cut. No metal particles could be placed in the fill without being contained within a rubber segment. Ends of metal belts and beads were expected to be exposed only in the cut faces of some tire shreds." Upton and Machan (Ref. 47) note that the TDA fill contained oversize pieces and excess metal fragments.

The TDA was placed in 1-m (3-feet) lifts and compacted with three passes of a Caterpillar D-8 bulldozer. A Caterpillar D-6 bulldozer was also tried, but it appeared to be less effective than the D-8. Side slopes were trimmed with an excavator. The TDA was separated from the surrounding soil with a geotextile. The maximum thickness of TDA fill was about 4.3 m (14 feet). At one point during construction, a 2.4-m (8-foot)-high vertical face of TDA was exposed and remained stable. After compaction, but before placement of the overlying soil cover, the TDA unit weight was estimated to be 0.72 Mg/m^3 (45 pcf). The overlying cover consisted of 0.91 m (36 inches) of soil,

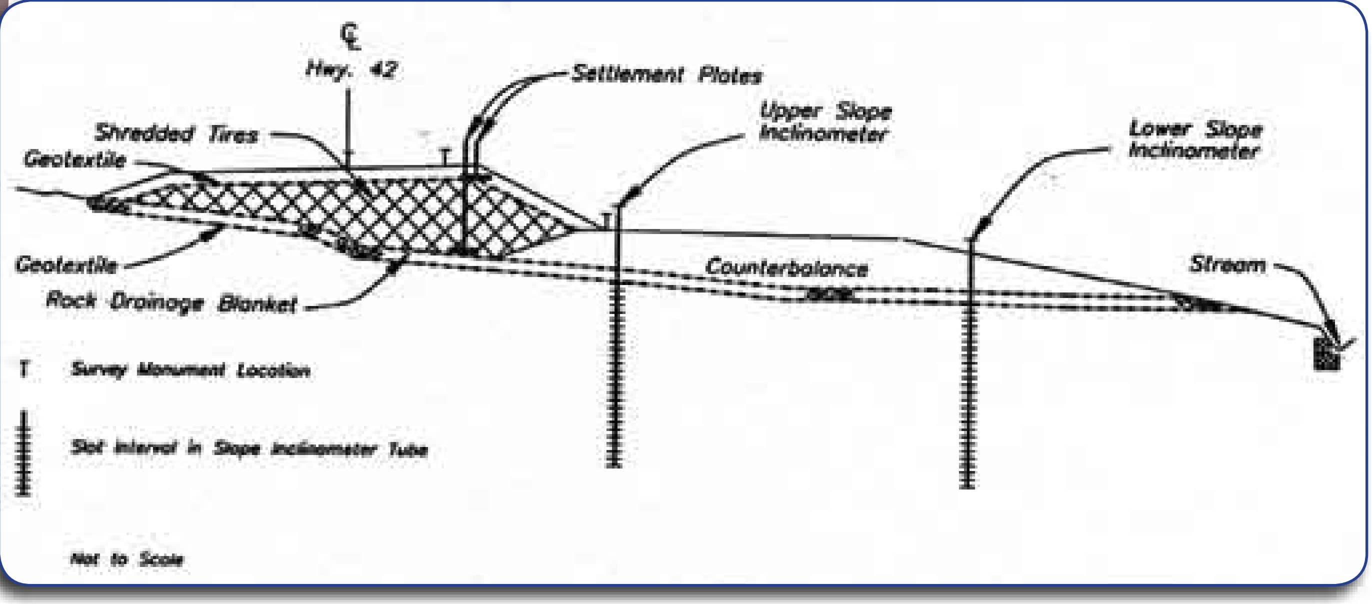


Exhibit. 5-5. Cross section through Oregon tire shreds field trail (Ref. 47)

0.58 m (23 inches) of aggregate base course giving a total soil cover of 1.50 m (59 inches). The overlying pavement was 200-mm (8-inches) thick. After compression under the weight of overlying material, unit weight was estimated to be 0.85 Mg/m^3 (53 pcf).

Wall Backfill

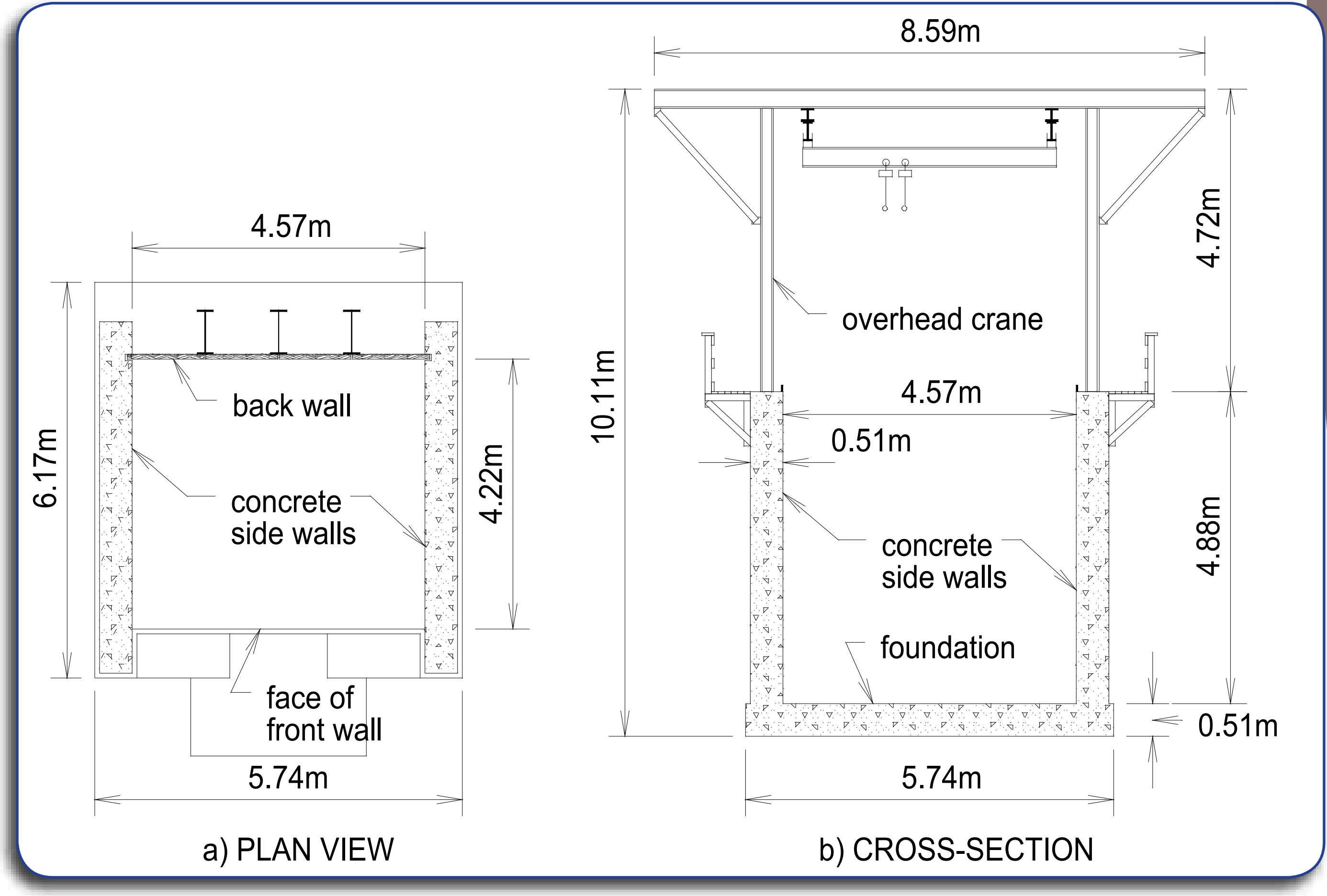
There are several advantages to using TDA as backfill behind walls, including reduction in horizontal stress, reduction in vertical stress on compressible foundation soils, and improved drainage. The design guidelines for use of TDA as wall backfill are largely derived from a full-scale test conducted at the University of Maine, as described in the following subsections (Refs. 44, 45).

Facility Design

The test facility is 4.88 m (16 feet) high and 4.47 m by 4.57 m (14.7 feet by 15 feet) in plan. It consists of four walls and a reinforced concrete foundation. The two sidewalls are reinforced concrete. The back wall is removable, which allowed the backfill to be removed after a test had been completed. The front wall consists of three panels. Forces and pressures were measured on the center panel to reduce the influence of friction between the backfill and the sidewalls. The center panel was mounted on six load cells: two oriented vertically at the base of the panel to measure the shear force; and four oriented horizontally, two at the bottom of the panel and two at the top, to measure the horizontal force. The center panel also contained four pressure cells cast into its concrete face. Outward rotation of the three panels about their bases was controlled using screw jacks. Concrete blocks were used to apply surcharges up to 35.9 kPa (750 psf). The facility design is shown in Exhibits 5-6 and 5-7.

TDA Properties

TDA from three suppliers were tested. The TDA from Pine State and Palmer was long and flat with many exposed steel belts, while TDA from F&B was equi-dimensional with few exposed steel belts. The TDA was uniformly graded and composed primarily of gravel-size particles. Gradation of the TDA showed that F&B TDA was the smallest with a 38-mm (1.5-inches) maximum size, while the maximum size of both Pine State and Palmer TDA was 76-mm (3-inches). The TDA was placed in 200-mm (8-inch) lifts and compacted with four passes of a walk-behind vibratory tamping



a) PLAN VIEW

b) CROSS-SECTION

Exhibit 5-6. Plan and cross-section of full-scale retaining wall test facility

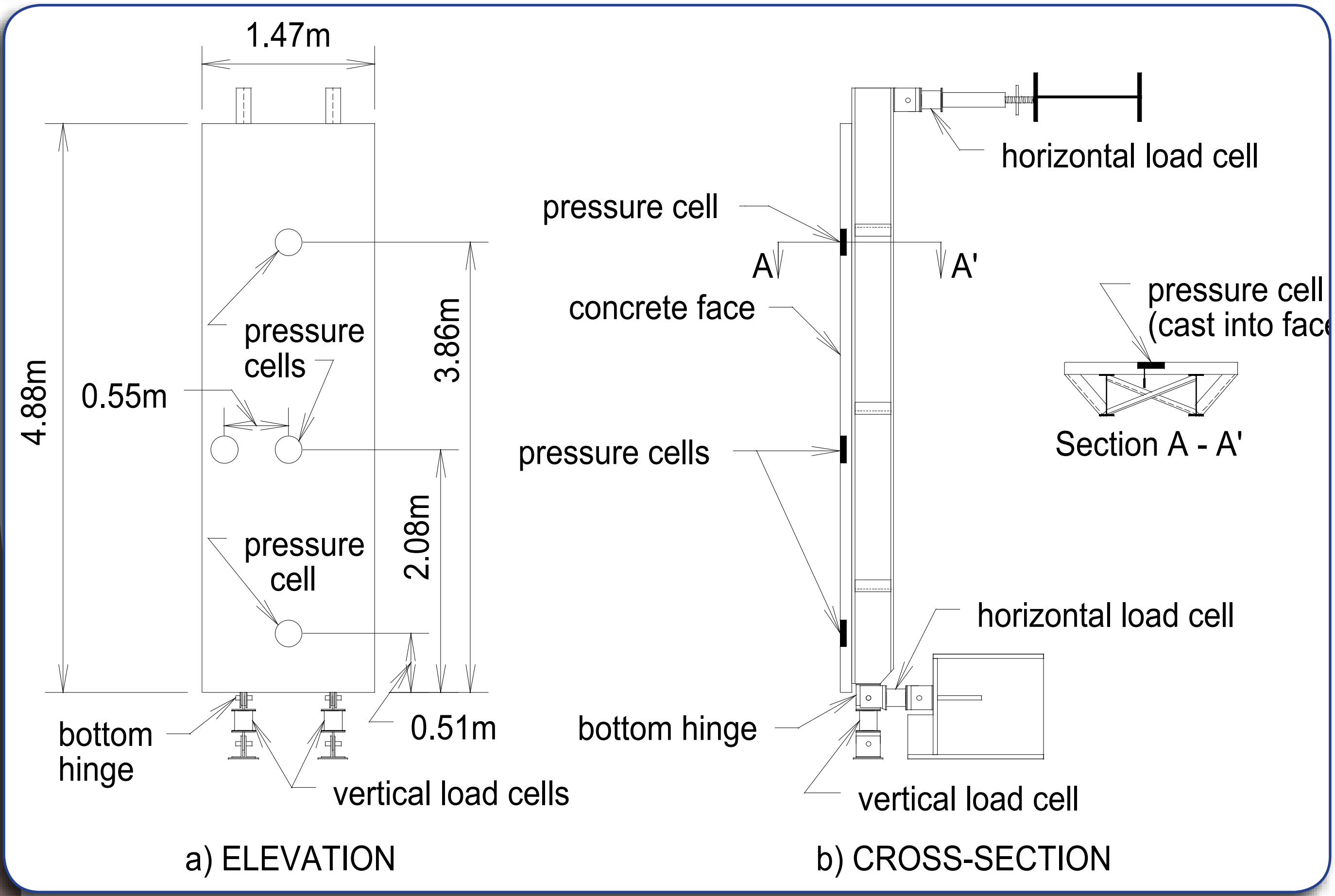


Exhibit 5-7. Elevation and cross-section for front wall center panel

foot roller with a static weight of 1,180 kg (2,600 pounds). The field density was measured by compacting a lift of tire shreds in a 3.05-m (10-foot)-long by 1.02-m (3.3-foot)-wide box. The average field density based on five tests was 0.71 Mg/m3 (44.3 pcf) for F&B, 0.69 Mg/m3 (43.1 pcf) for Palmer, and 0.71 Mg/m^3 (44.3 pcf) for Pine State.

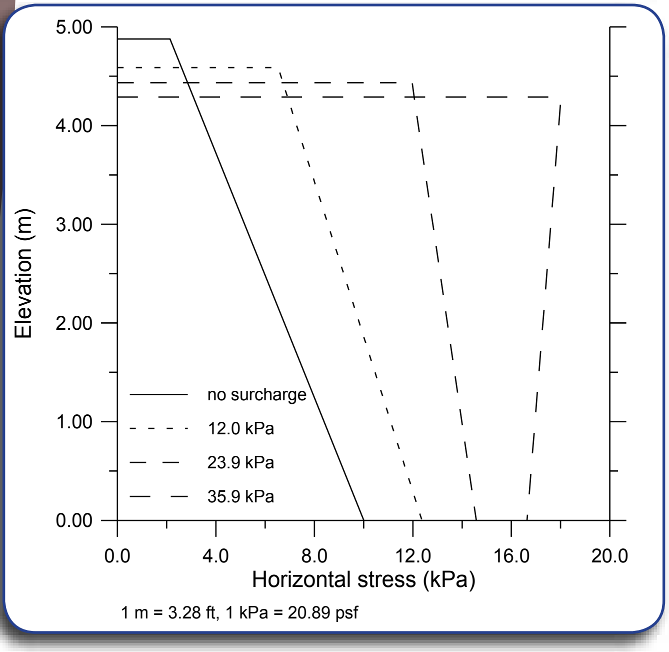


Exhibit 5-8. At-rest stress distribution for Palmer shreds at four surcharges

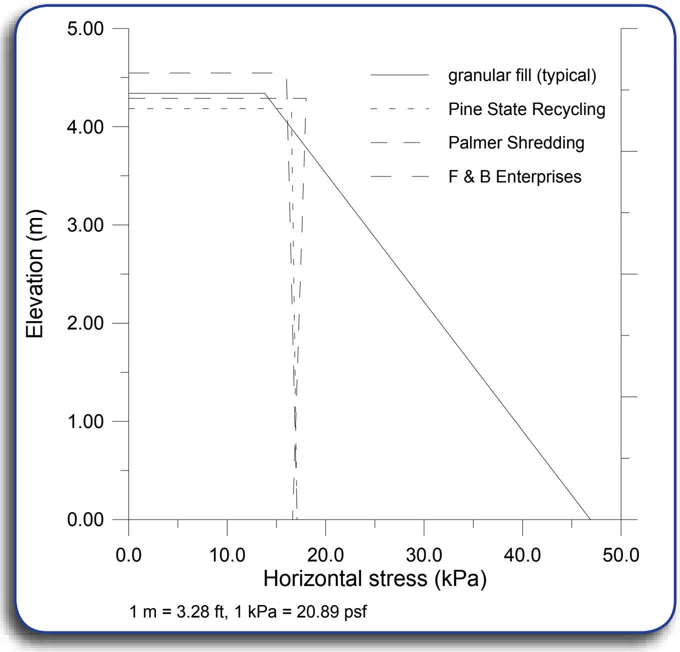


Exhibit 5-9. At-rest stress distribution at a 35.9 kPa surcharge compared with granular fill

Table 5-2. Coefficient of Lateral Earth Pressure at Rest, Ko

		Surcharge			
Supplier	**Depth (m)**	**0**	**12.0 kPa**	**23.9 kPa**	**35.9 kPa**
F&B Enterprises	0	0.99a	0.51	0.44	0.45
	2	0.39	0.33	0.32	0.32
	4	0.31	0.28	0.26	0.25
Palmer Shredding	0	0.94a	0.58	0.51	0.51
	2	0.37	0.33	0.27	0.33
	4	0.29	0.27	0.17	0.24
Pine State Recycling	0	0.93a	0.55	0.46	0.47
	2	0.37	0.32	0.32	0.32
	4	0.28	0.26	0.26	0.25
Average	0	0.95a	0.55	0.47b	0.47b
	2	0.38	0.33	0.31b	0.31b
	4	0.29	0.27	0.24b	0.24b

[a] Value found at a depth of 0.5 m (1.6 feet)
[b] Average from 23.9 kPa (500 psf) and 35.9 kPa (750 psf) surcharges

At-Rest Horizontal Pressure

The horizontal stress distribution was calculated using the load cell measurements by summing the moment forces about the base of the panel and assuming the distribution to be trapezoidal. The horizontal stress distributions for each of the suppliers were similar. A typical plot with Palmer TDA is shown on Exhibit 5-8. This exhibit shows that the horizontal stress increases with increasing surcharge. At the lower surcharges, the horizontal stress increases with depth, but the horizontal stresses becomes almost constant with depth at the higher surcharges.

The horizontal stress distributions of tire shreds and granular fill under the 35.9 kPa (750 psf) surcharge were compared. As part of the study, a granular fill was tested in the facility. However, the granular fill was well-graded gravelly sand. It was placed near optimum water content and therefore exhibited considerable apparent cohesion. This cohesion was evidenced by the granular fill standing on a 4.57-m (15-foot)-high vertical face when the back wall was removed. The apparent cohesion led to unrealistic values of horizontal stress. Therefore, the horizontal stress distributions at the 35.9 kPa (750 psf) surcharge for each of the tire shred suppliers were compared with the expected horizontal stress distribution for a typical granular fill with a compacted density of 2.02 Mg/m^3 (126 pcf) and a coefficient of lateral earth pressure at rest (Ko) of 0.38, as shown in Exhibit 5-9. The resultant of the horizontal stress from the tire shreds is approximately 45 percent less than for granular fill. This difference is a result, at least in part, of the density of tire shreds, which is one-third to one-half of conventional granular backfill.

The coefficient of lateral earth pressure at rest for TDA was calculated. For no surcharge, Ko was calculated just below the fill surface because the vertical stress is zero at the fill surface, so Ko is undefined. The values for Ko are summarized in Table 5-2, which shows that the coefficient of lateral earth pressure at rest decreases with depth for all four loading conditions. The values for Ko also decrease from no surcharge to 23.9 kPa (500 psf). Ko then remained approximately constant from 23.9 to 35.9 kPa (500 to 750 psf). The differences between Ko for each supplier at a given surcharge and depth are small. Comparison of Ko for TDA shown on Table 5-2 with typical Ko of normally consolidated granular soils of 0.35 to 0.50 (Ref. 14) shows Ko for TDA is lower at the 2.0 m (6.6 feet) and 4.0 m (13.1 feet) depths. This comparison also suggests that the lower at-rest pressures produced by TDA are a result of both their lower Ko and their lower density.

Active Earth Pressure

After measurements for the at-rest condition were completed, the wall was rotated outward to achieve active earth pressures. The horizontal stress distributions for all of the suppliers at the same wall rotation were similar. The horizontal stress distributions immediately after each wall rotation for Palmer TDA under an applied surcharge of 35.9 kPa (750 psf) are shown in Exhibit 5-10. Before rotation,

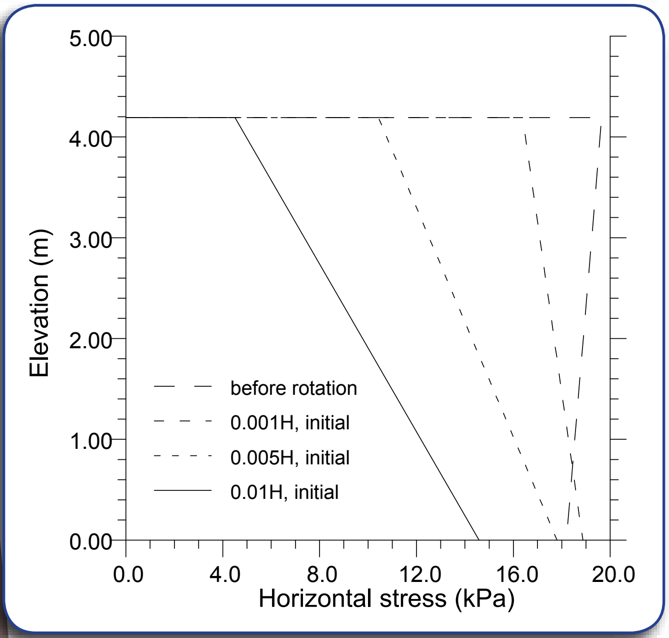


Exhibit 5-10. Stress distribution for Palmer shreds for wall rotations of zero to 0.01H

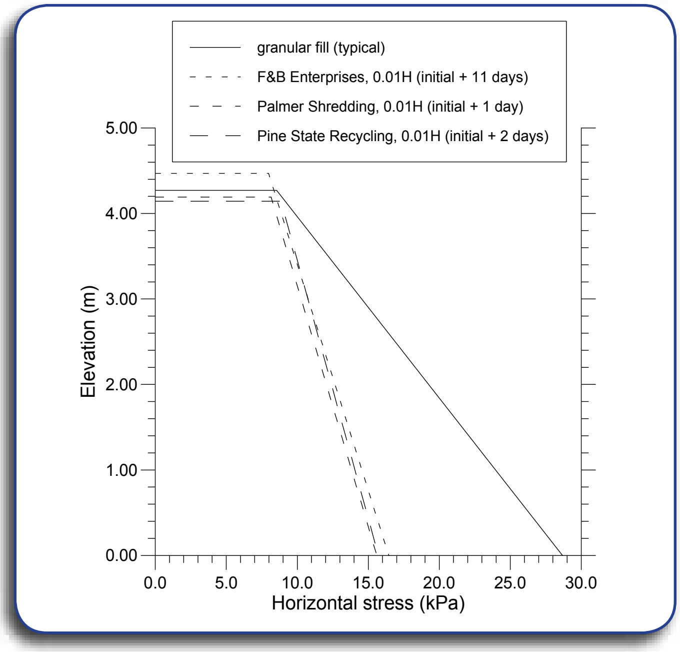


Exhibit 5-11. Stress at 35.9 kPa surcharge and 0.01H rotation compared with granular

the horizontal stress decreases slightly with depth; then, as the wall is rotated from at-rest conditions to 0.01H (H is the rotation factor as a function of the wall height), the horizontal stress decreases significantly at the top. At a rotation of 0.01H, the magnitude of the resultant horizontal force was 50 percent less than before rotation. Similar decreases in horizontal stress were measured for F&B and Pine State. The horizontal stress for TDA at a rotation of 0.01H was compared with a typical granular fill with a compacted density (ρ) of 2.02 Mg/m^3 (126 pcf) and a coefficient of lateral earth pressure at rest (Ka) of 0.24, as shown in Exhibit 5-11. The resultant horizontal force from the TDA was approximately 35 percent less than that of the granular fill.

The earth pressure coefficient, K, was calculated for each TDA supplier at the 0.01H rotation and the larger rotations for Palmer and Pine State at depths of 0 m, 2.0 m, and 4.0 m. The results are shown in Table 5-3. It is seen that for a rotation of 0.01H, K is similar for the three suppliers at each depth, with values ranging from 0.22 to 0.25 kPa. At larger rotations, K ranges from 0.16 to 0.18 kPa at a rotation of 0.03H for Palmer and from 0.08 to 0.12 kPa at a rotation of 0.04H for Pine State. These values suggest that K decreases with outward movement. Exhibit 5-12 shows that the effect of wall rotation on K is greater at the shallower depths. Moreover, reduction in K is small for rotations greater than 0.01H, suggesting that the reported K values were approaching the minimum values that meet the definition of active conditions. A reasonable approach for design would be to use the K for a rotation of 0.01H. Thus, a design K of 0.25 kPa would

Table 5-3. Earth Pressure Coefficient, K for Rotated Case

Supplier	Depth (m)	Rotation		
		0.01H	0.03H	0.04H
F&B Enterprises	0	0.23	- -	- -
	2	0.23	- -	- -
	4	0.23	- -	- -
Palmer Shredding	0	0.23	0.18	- -
	2	0.22	0.17	- -
	4	0.22	0.16	- -
Pine State Recycling	0	0.25	- -	0.08
	2	0.23	- -	0.11
	4	0.22	- -	0.12

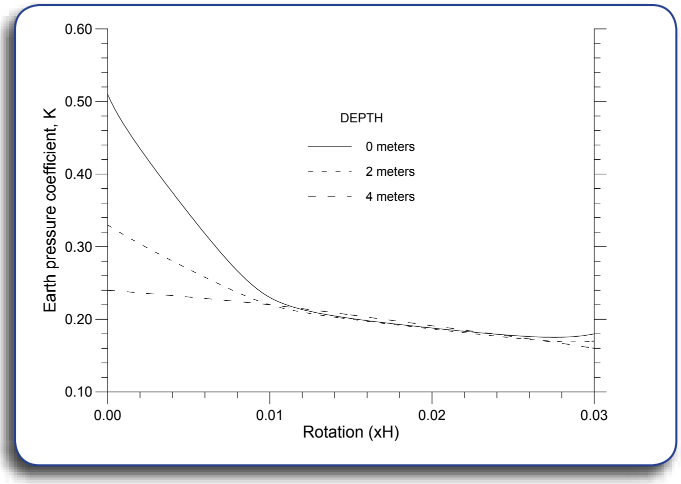


Exhibit 5-12. Effect of rotation on earth pressure coefficient at 35.9 kPa (750 psf) surcharge

be reasonable and slightly conservative compared the values in Table 5 for conditions similar to this trial.

A simplified design approach was developed based on equivalent fluid pressure. The semiempirical design parameters were developed following the methods presented in Terzaghi and others (Ref. 42) for soils. The key parameter is a semi-empirical value, kh, with units of weight per unit volume. The method can be thought of as replacing the backfill with a fluid of density kh. The value kh can then be used to calculate the horizontal stress using:

$$\sigma h = gkhd \qquad \text{(Eq. 1)}$$

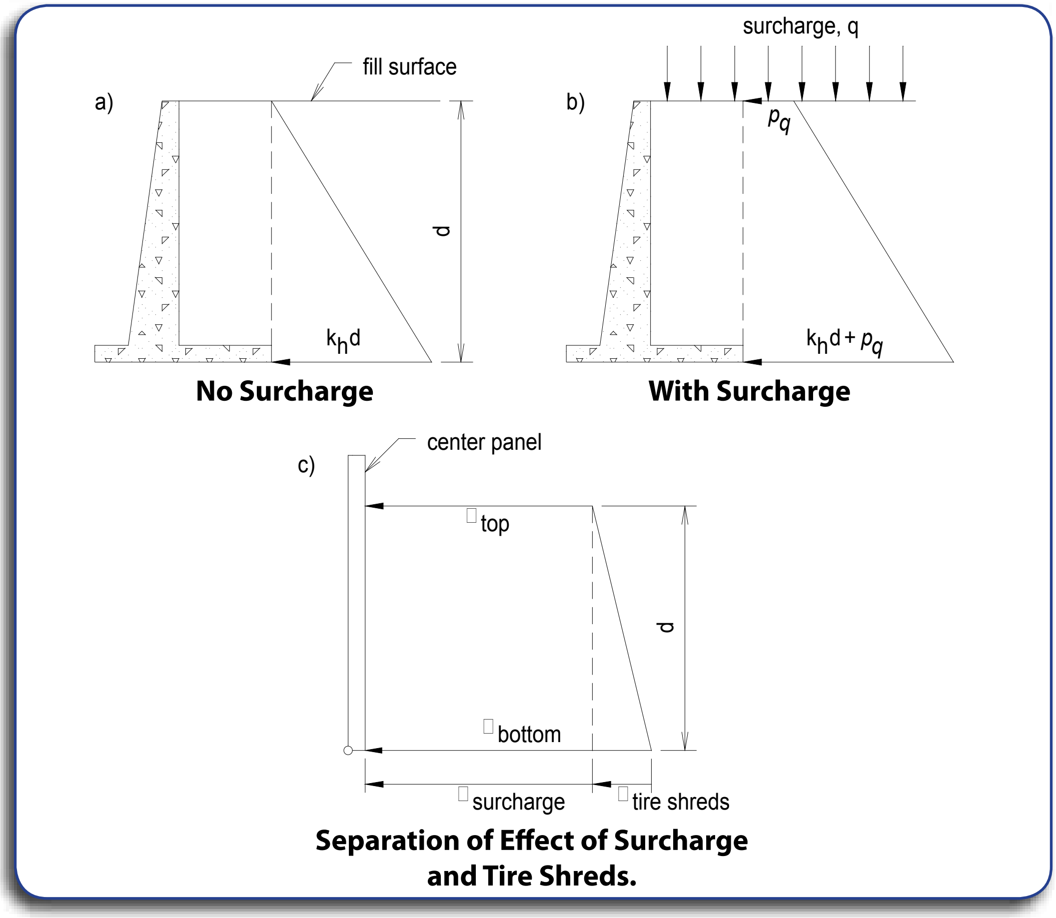
where g is gravity, 9.81 meters/second2 (m/s^2), and d is the depth of the fill, as shown on Exhibit 5-13a. In cases where a surcharge is applied and the surface of the backfill is horizontal, the horizontal stress at any depth is increased by the amount:

$$p_q = Cq \text{ (Eq. 2)}$$

where C is a coefficient dependent on the backfill type, and q is the surcharge in units of load per unit area. The combination of the stress caused by the backfill and the surcharge results in a trapezoidal

Table 5-4. Semiempirical Design Parameters for Rotation of 0.01H

Supplier	k_h (mg/m3)	C
F&B Enterprises	0.19	0.22
Palmer Shredding	0.18	0.23
Pine State Recycling	0.17	0.25



No Surcharge

With Surcharge

Separation of Effect of Surcharge and Tire Shreds.

Exhibit 5-13. Semiempercal design procedure distribution, as shown on Exhibit 5-13b. The values kh and C were found by dividing the trapezoid distributions determined from the load cells into two parts, as shown on Exhibit 5-13c. The contribution to the horizontal stress from the tire shreds was taken to be the triangular portion of the distribution, shown as $\sigma_{\text{tire shreds}}$. The remainder of the horizontal stress was assigned to the $\sigma_{\text{surcharge}}$. The results for a rotation of 0.01H are shown in Table 5-4. It would be reasonable to use a kh = 0.18 Mg/m^3 (11 pcf) and C = 0.23 for design for conditions similar to this study. For comparison, the kh for granular backfill is about 0.5 Mg/m^3 (31 pcf) (Ref. 42).

Sample retaining wall using whole tires
Photo courtesy of La Comisión Estatal de Servicios Públicos de Tecate

Whole tire wall used to impede soil erosion
Photo courtesy of La Comisión Estatal de Servicios Públicos de Tecate

WHOLE TIRES FOR WALL CONSTRUCTION

Whole tires can be used to construct low retaining walls (Refs. 6, 35, 39, 50), along slopes as an erosion control method, or in wetland retention design. One system of wall construction proposed by the California Department of Transportation is shown in Exhibit 5-14 (Ref. 6), although there are many other methods of construction in use today. The tires are filled with compacted soil and in each given layer are hooked together with metal clips made from bent rebar. The adjoining layers are then connected by driving recycled metal delineator posts within the compacted soil. Erosion is of great concern for much of northern Mexico, as its arid climate does not

Example of the erosion that is possible with the conditions in Northern Mexico
Photo courtesy of La Comisión Estatal de Servicios Públicos de Tecate

The Use of Scrap Tires as a Method of Erosion Control in Mexico

One study completed by El Instituto Tecnológico y de Estudios Superiores de Monterrey tested the efficiency of scrap tires used along slopes with poor growing conditions where erosion is a problem. In measuring sediment eroded for slopes both with and with out scrap tires they found in 82 percent reduction in erosion along the slopes that used the proposed system of scrap tires strung down the slope. The tires were also found to help retain moisture and aid in vegetative growth along the slope, further decreasing erosion. Wild grass was observed growing in 85 percent tire zone test areas compared with 10 percent growth in other areas. The institute concluded that there was no evidence of an increase in mosquitoes in the area caused by the use of tires, there was an overall decrease in maintenance costs and closures of slope areas as a result erosion, and at the time of the study (2006) the total system could be implemented for about $11.6 pesos (U.S. $0.90) per tire. For further information, contact Dr. Martin H. Bremer, Profesor Investigador en Sistemas Geoambientales at mbremer@itesm.mx.

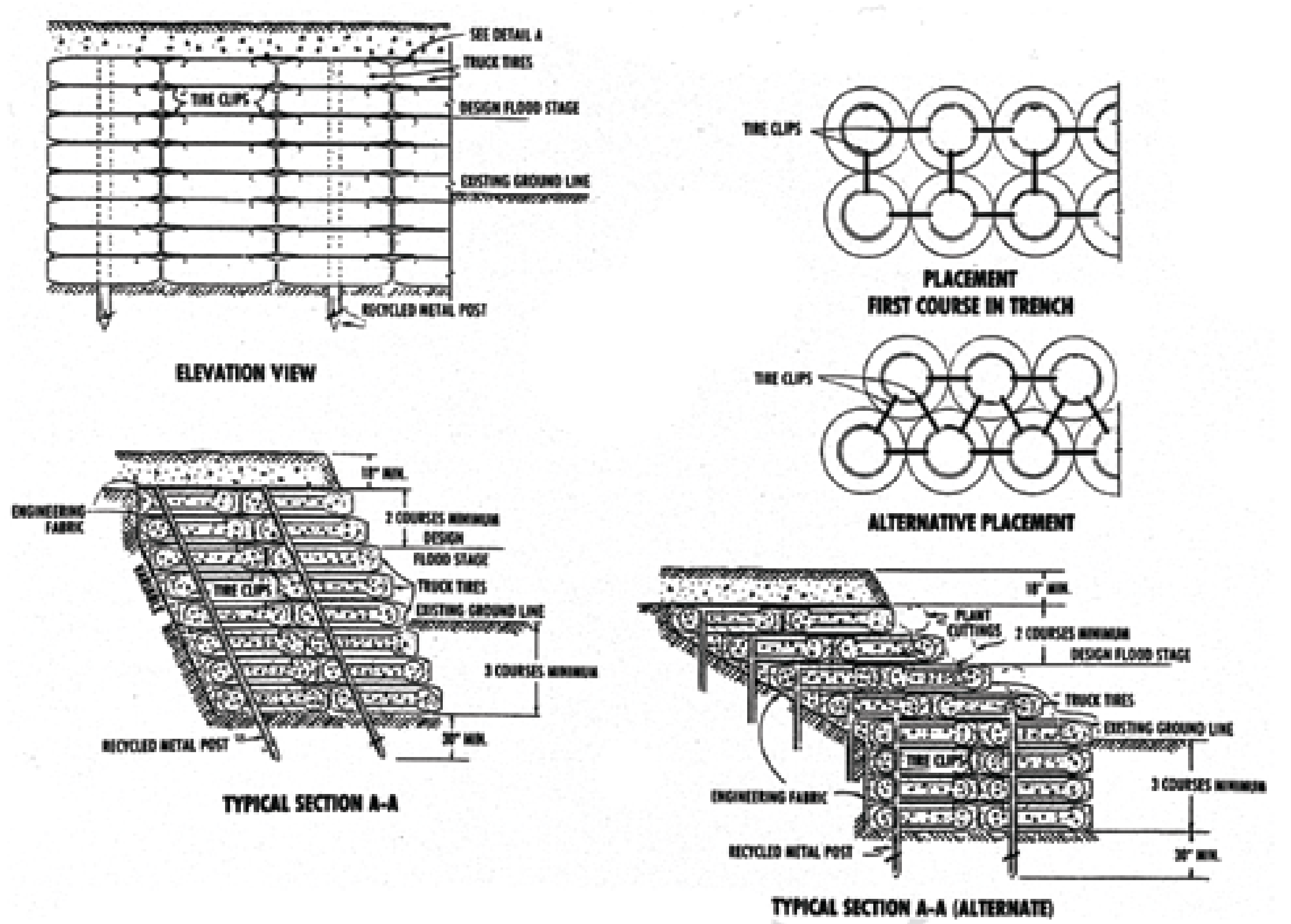


Exhibit 5-14. Retaining wall system constructed from whole tires (Ref. 6)

readily support vegetative growth and the elevated landscapes create optimal conditions for erosion. Erosion in densely population areas can be dangerous and expensive to control. It can cause closure of and increased maintenance on roadways and affect housing built on or near eroding slopes. The use of scrap tires has been shown to be effective in the area of erosion control and can provide a low-cost solution for reuse of the scrap tires in the area.

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CHAPTER 6

Transportation and Processing Economics

The preceding chapters focused on major applications, or specialized uses, for scrap tire resources because markets define the required collection and processing methods. Collection can be local for small, nearby markets, or regional, for large markets and centralized processing facilities. Scrap tires can be used whole or processed into pieces ranging from large civil engineering chips to fine crumb rubber, with differing processing requirements for each size. Collection and processing systems naturally evolve with markets, but the probability of succeeding with limited resources is maximized by targeting defined initial market needs. The following section provides a brief discussion of basic collection, transportation, and processing (including methods, equipment, processes, and economics) to assist in evaluating alternatives. The discussion is based on historical experience in the United States, but U.S. economics have been converted into comparable Mexican economics to make them more applicable to the projected market and economic structure in Mexico and increase their usefulness in Mexico. This section is based on 2008 costs and may vary depending on present market values.

COLLECTION AND TRANSPORTATION

Scrap tire collecting and hauling are critical components in effective use of the tire resource. The impact of efficient collection on the economic viability of scrap tire management alternatives is often underestimated. Hauling, on the other hand, will evolve with the management program. If no regulations or enforcement exist to govern tire disposal, transportation costs will encourage discarding them at the closest site, especially for small collection vehicles such as pickup trucks. Small vehicles generally represent the highest risk for illegal tire disposal in the United States. However, once regulations are in place and enforced, competitive pressure will force the use of efficient collection methods and vehicles. Inefficient haulers will fail.

Methods

Scrap tires are normally generated where replacement tires are installed, such as at tire stores, car dealerships, and repair shops. Tires are a naturally segregated waste stream unless they are mixed with other wastes intentionally. In the United States, they are generally collected separately, without contamination from other materials, by people or companies that specialize in tire collection. Reusable casings are removed for resale, and the rest are properly disposed of at processing facilities or landfills if appropriate regulations, penalties, and enforcement are in place. Otherwise, the remaining tires are too often dumped or stockpiled because these disposal options are the lowest cost.

Tires can be collected on scheduled intervals or an as-needed basis. Route collection generally involves trucks travelling scheduled routes at designated frequency, with tires loaded by the driver, an assistant, or store personnel. Tires are counted during loading for invoicing. Collection can be requested as needed rather than on a regular schedule for stores with small or variable generation. Charges for this type of pickup are generally based on the number of tires, distance, and other factors.

Trailers are often parked at stores with high volumes and adequate space. The trailers are loaded by store employees and locked to prevent vandalism, dumping, and arson. When the trailer is full, the store notifies the collector and an empty trailer is delivered at the same time that the full trailer is removed. The store is generally charged a fixed fee per trailer based on distance, turnover frequency, gradable casings, and other cost-sensitive factors. Dumpsters and bins have also been used, but limited capacity and inefficient hauling make these alternatives expensive. In all cases, the hauler is paid by the store or by the government to haul the tires to an acceptable disposal site based on the requirements of the waste tire program that is used in the area.

Equipment

A wide variety of vehicles have been used to haul tires, anything from wheelbarrows to diesel tractors. The following is a brief discussion of some commonly used vehicle types.

Pickup Truck

Pickup trucks are a common vehicle capable of hauling many materials, including scrap tires. Carrying capacity for full-size pickups ranges from

Box truck for tire transportation
Photo courtesy of Tire Recycling and Disposal, Inc.

about 450 to 900 kg (1,000 to 2,000 pounds), depending on model and condition. The bed can hold the equivalent of up to 50 passenger tires (10 medium truck tires) if properly laced or stacked. These tires weigh approximately 1,000 pounds, the normal carrying capacity of basic half-ton (sometimes called 150-class) pickups in good condition. A metal cage can be added to increase the containment volume if the pickup has sufficient load carrying capacity. Some 0.7 metric ton and 0.9 metric ton (called 250- and 350-Class) pickups can carry 900 kg (2,000 pounds) or more. A caged trailer can be used to optimize hauling capacity because most pickups can tow more weight than they can carry within the truck itself. Towing capacity generally ranges from 2,250 to 4,550 kg (5,000 to 10,000 pounds), representing 250 to 500 passenger tires. Since most manageable trailers cannot hold that number of tires, trailer volume generally controls towing capacity.

Box Truck

Box trucks are commonly used for local waste tire collections. They can hold up to 400 passenger tires if tightly laced. Examples of a box truck and proper lacing techniques are shown in the photos to the right.

The driver typically travels a designated route, stopping to load tires from regular customers or those requesting service from a dispatcher. Infrequently, cargo vans or an open cage welded onto a flatbed truck have been used as alternatives.

Tractor Trailer

Traditional tractor trailer rigs are commonly used for collection and transport of large volumes of tires. Capacity for whole tires is limited by volume and depends on the trailer size, tire types, loading methods, and contamination. It ranges from 500 to 750 tires in a 27-foot tandem trailer to more than 1,500 stacked in laced fashion in a 52-foot trailer. Processing reduces the tire volume by a factor of two to five, so processed tire loads are normally limited by maximum weight allowances, and not volume. Normal payload limits are 22 to 26 U.S. tons (2,200 to 2,600 passenger tire equivalents) in the United States, based on total weight limits minus the weight of the tractor and empty trailer. Tandem trailers further increase tire capacity for long hauls when local regulations allow them.

Collection/Hauling Economics

Tires can be collected and hauled by whatever vehicle is available, but experience and the competitive nature of the business have led good operators to carefully evaluate optimum equipment for specific purposes. To illustrate the differences, capital and operating costs associated with collecting and hauling tires about 30,000 miles a year were calculated for each major type of equipment. Since all of these costs vary significantly with time and location, this information should be used only for comparison or as a basis for recalculation using local economic conditions. The example assumes the purchase of used equipment in good condition with estimated labor, maintenance, and fuel costs based on some areas in the United States. Estimated insurance, depreciation, and a 20-percent annual return on investment have been included in the fixed cost calculations, but interest was not included for any funds borrowed. The initial U.S.-based economics are included in Appendix H for reference by those in border areas. In addition, a Spanish version of these

Proper lacing technique for tire transportation
Photo courtesy of Tire Recycling and Disposal, Inc.

economics adjusted to reflect economics within Mexico is also included in Appendix H.

The capital and operating costs were estimated for a pickup truck, a pickup with a caged trailer, a box truck, and a diesel tractor with a 48-foot trailer. For simplicity, it was assumed that the vehicle averages 48.28 km/hour (30 mph), allowing time for tire loading along the way. The costs were calculated on a cost/km basis, and then reduced to cost/km/tire to more accurately reflect volume economics. The data is provided in Appendix F at the end of this chapter.

Exhibit 6-1 summarizes the capital and operating costs ($/mile) for each of these alternatives. As expected, both costs increase with size of the vehicle. However, cost/km/tire is a better indicator of hauling efficiency than is cost/mile. Exhibit 6-2 provides the cost/tire for hauls of 25, 100, and 500 miles for comparison, again based on the data shown in Appendix F. Pickup trucks are expensive on a cost/tire basis even on short hauls, but become prohibitive on longer trips. A caged trailer improves capacity and efficiency, but practical service range is generally 100 to 150 miles. Box trucks are slightly more efficient, but are normally used for total travel distances of less than 200 miles. Tractor trailers are the most efficient choice for longer distances. Longer trailers (52 feet) or tandem 27-foot trailers are most efficient if roads and regulations allow them.

These calculations also assume that the vehicle is filled up during the trip. The cost/tire will increase if it is not filled, so a smaller vehicle may be better in these cases. In some cases, it may be most efficient to establish a collection point in a town or area where tires can be accumulated and then be hauled in larger vehicles to regional processing facilities or markets.

PROCESSING

Tires must withstand impact and high speeds while on vehicles, and they have to do so at temperatures ranging from subzero to desert heat. The flexibility of rubber, combined with the strength and abrasiveness of reinforcing steel, makes tires a challenge to process for product applications. The following section discusses basic tire processing and economics as a generic framework for individual evaluations.

Scrap tire processing covers a broad range of methods and equipment. This discussion focuses on large markets that can use whole tires and shredded tires ranging from large Type B TDA (See Chapter 3 for discussion of Type B TDA) to nominal 2.5-cm (1-inch) TDF (discussed in the Energy Utilization Section) and the equipment commonly used to produce these products. Additional equipment that can be added to further reduce product size for ground rubber applications is also discussed. Capital and operating costs associated with this additional equipment are substantial.

Critical Issues

Many U.S. scrap tire processors, and especially ground rubber producers, have historically failed within 1 to 5 years after they enter the business. Many of the failures may have been avoided by considering the following issues before any investment decisions were made:

Product Markets

The rate of market development for scrap tire products has historically limited the growth of tire processing. Elapsed time and costs associated with market development are generally underestimated and have a major impact on the economic viability of processors. The time required to develop markets can be years, not weeks, and may require customer identification and acceptance, regulatory approval, product testing, market introduction, and distribution development. Accumulating product inventory while markets develop is doubly expensive because it decreases revenue anticipated from product sales while increasing working capital requirements. The combined result can lead to failure of an otherwise well-conceived operation because, sooner or later, either financial resources or regulatory agencies will limit the inventory of products and tires at a processing site.

Product Specifications

Time spent defining product specifications and processing requirements before investment decisions generally saves money in implementation and minimizes subsequent, expensive changes. Equipment that may be appropriate for one application can be technically or economically unsuitable for another. Considering the evolutionary stages for markets and products can improve the probability that initial equipment purchases will have the flexibility to serve future needs. Properly evaluating product volumes, specifications, and timing are probably the most critical, and commonly ignored, steps in establishing a successful processing operation.

Product Pricing

Apparent scrap tire product pricing may be lower in practice for these important reasons:

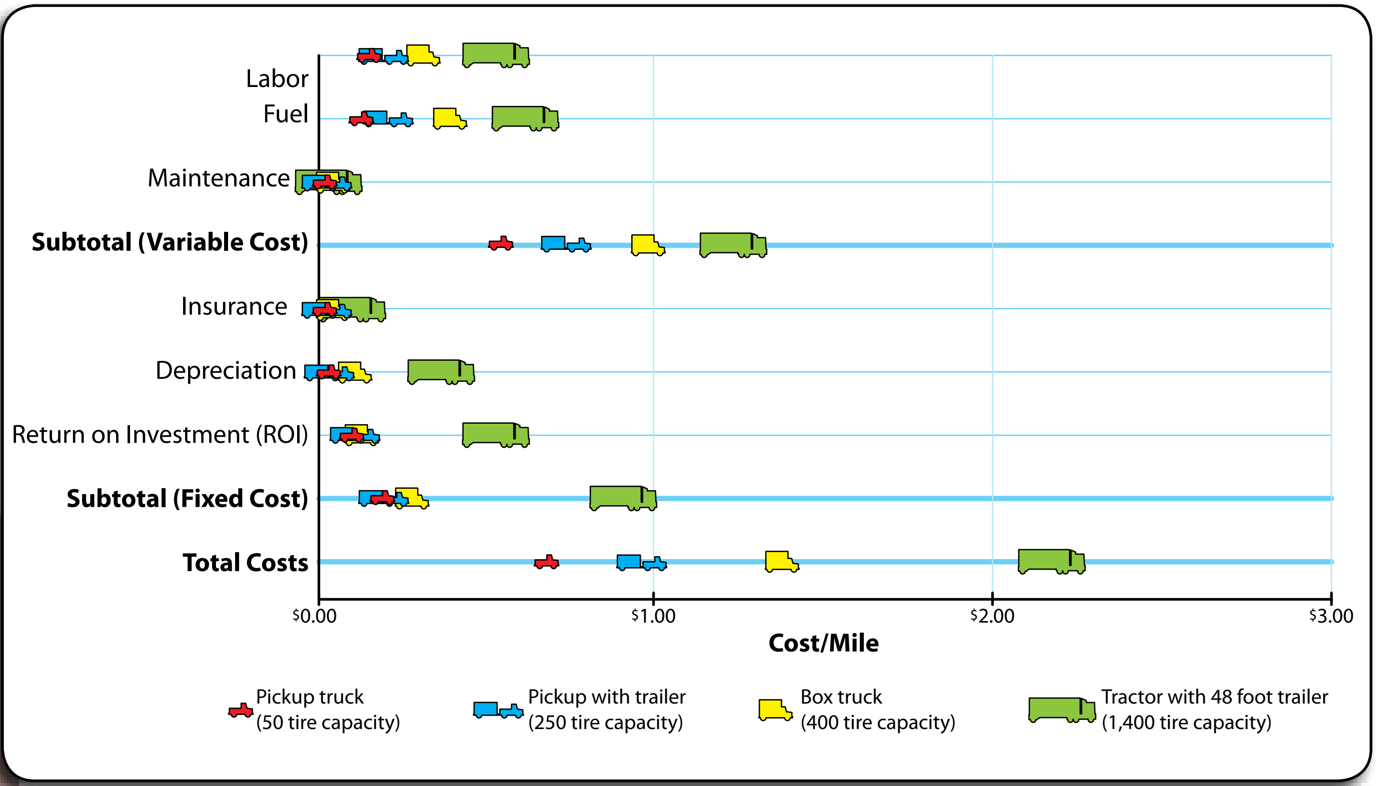


Exhibit 6-1. Capital and Operating Cost Comparison (Cost/Mile)
(See Appendix F for specific data)

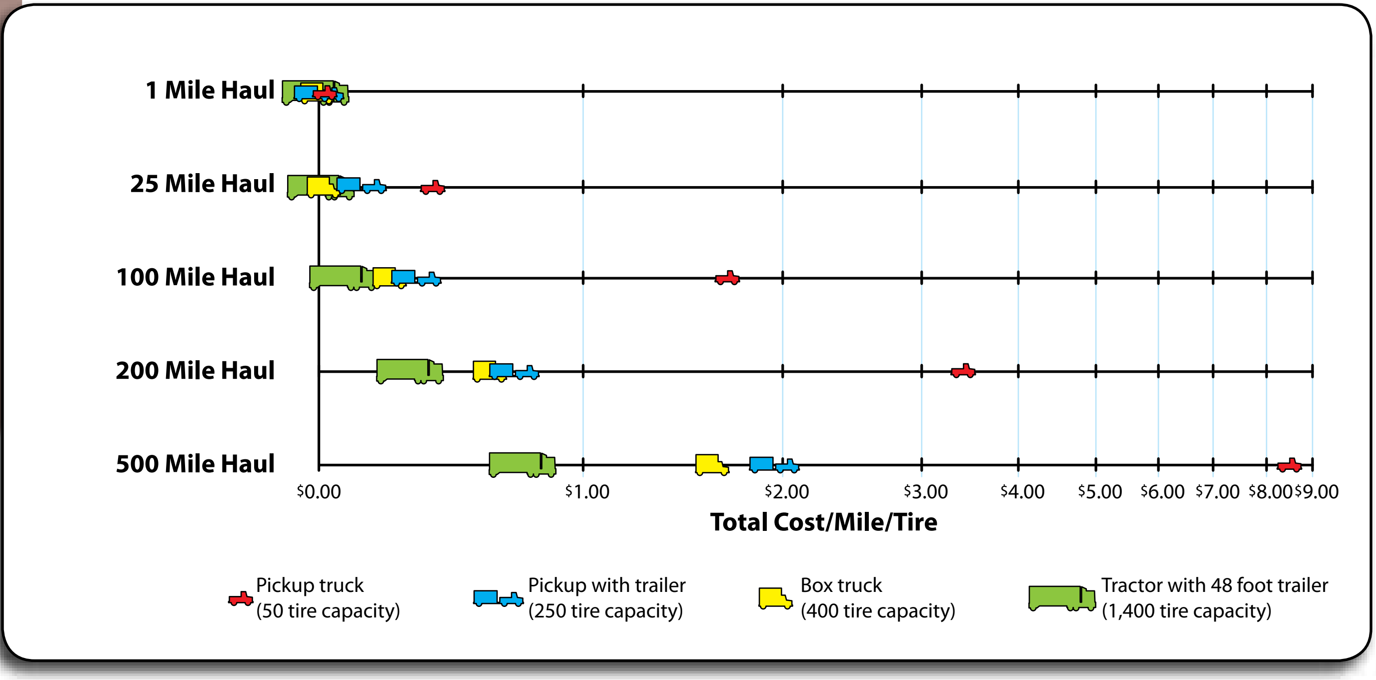


Exhibit 6-2. Hauling Efficiency (Cost/Mile/Tire)
(See Appendix F for specific data)

(1) Pricing quoted on a delivered basis for competitive reasons may include significant transportation costs. Therefore, transportation expenses reduce the net revenue received by the recycling facility. For example, at $2.00/mile and 40,000 pounds/truckload, one-way trucking costs are about $0.01/pound for each 200 miles covered and would double if the truck returns unloaded. Additionally, transportation costs to distant markets from remote facilities can be expensive, reducing or eliminating any profit from these sales.

(2) Current pricing may be negatively affected by competitive efforts to displace current suppliers from existing markets. A new supplier often has to offer an economic advantage to be considered, causing a price shift across all markets and cutting into profit margins.

Government grants and subsidies can be helpful in developing applications and processors, but government must develop a sound plan to avoid negative impact. For instance, government grants for processing equipment can be counter-productive by creating unfair competition between existing processors who purchased their own equipment and new producers who receive free equipment through grants. The existing producer may fail due to its economic disadvantage and the new producer may also fail due to lack of operating experience. Market subsidies can also be counter-productive by creating false economics. Many subsidized markets are unable to survive when subsidies are eventually discontinued.

Raw Material Supply – Process and equipment requirements depend on the type and quantity of waste tires to be processed. Passenger tires are considerably easier to process than steel belted truck tires. This is especially true with the introduction of new, long-life truck tire carcasses that contain higher percentages of reinforcing wire. However, passenger tires contain more reinforcing fabric that can hinder ground rubber production and white lettering pigments that result in white specks in ground rubber. New "super single" medium truck tires substitute one larger tire for two regular truck tires, but these tires can be difficult to shred because of their greater width. If a specific type of tire casing is required, producers should consider whether it is readily available now and in the future. In many of the less populated areas, tire availability is a controlling factor.

Processing Equipment/System Design – Most scrap tire processing systems are conceptually simple and represent a balance of required economics, productivity, and product quality. Economic compromises may be self-defeating if salable product is not consistently produced. In developing tire processing systems, multiple components are normally assembled in series, with the design of each component optimized for its specific task. However, the impact of series operation on overall system reliability is often ignored. When multiple components are integrally interlocked in series, overall system reliability generally becomes the product of each component's reliability. For instance, the overall reliability of a process using five interlocked components with individual 90 percent operating factors will be 0.9 x 0.9 x 0.9 x 0.9 x 0.9, or 59 percent. When a system is designed with this perspective, overall productivity can be enhanced by separating sections with interim storage to allow partial production when one section is not functioning.

Placing equal emphasis on performance of all components can also improve productivity, even in comparatively simple systems. Attention is often focused on major equipment, while simple equipment such as conveyors and transfer points become afterthoughts. However, improperly designed transfer points that clog frequently can have a greater impact on system productivity than inadequate shredder maintenance.

These are just a few of the major issues that should be considered before a process is developed or equipment is selected. Many of the early processors in the U.S. failed because of the absence of markets, bad equipment choices, intense price competition, poor quality products, and bad operating practices. Subsequent successful operations have generally evaluated markets, equipment, and economics before they make an investment and have learned the value of proper maintenance and product quality control. Unfortunately, some processors continue to damage markets by unreliably supplying poor-quality products until both the processor and the markets fail. It is generally far less expensive to define critical parameters before the system is built than it is to modify, or completely rebuild, the system later.

Methods and Equipment

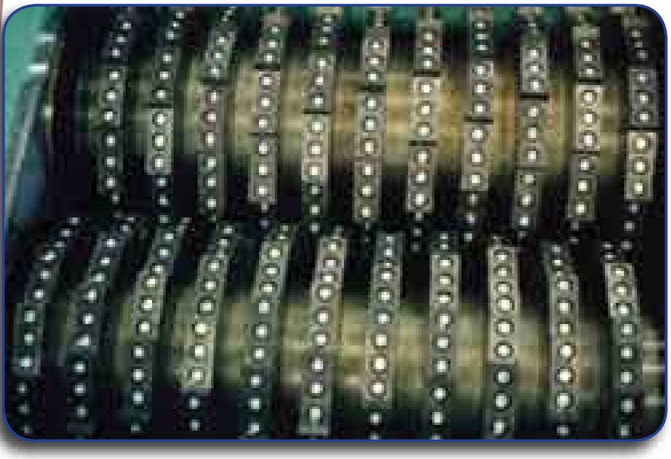
There is a broad selection of commercially available tire processing equipment, but it generally falls into

"Hook shear" type shedder
Photo courtesy of Granutech Saturn Systems Corporation, Dallas, TX

one of the three major functional classifications discussed below:

Size Reduction

The first step in tire processing is shredding to reduce the tire's size. Most shredders contain rotors that consist of a series of alternating cutting discs and spacers slipped onto a shaft. Two rotors are mounted within a cutting chamber, with the cutting disc of one rotor facing a spacer from the other rotor. These are called opposing rotors because the tops of both rotate toward the center, drawing tires between the close-tolerance knives and sheering them into strips. Some shredders use a single rotating shaft to draw and shear tires through stationary knives. Critical variables and operating parameters in shredders include:



"Detachable knife" type shredder
Photo courtesy of Columbus McKinnon Corporation, Sarasota, FL

Knife Type – Shredders generally use either: (1) integral discs with a series of extended metal hooks on the outside edge called "hook-shear" shredders, or (2) discs with attachable metal cutting blocks bolted onto the exterior perimeter called "detachable knife" shredders. Both operate at low speed and high torque to shear the tires between the knives. Examples of the hook shear and detachable knife shredders are pictured in this section.

Knife Width – Knife width is generally about 5 cm (2 inches). Knives can be stacked against each other to create a 10-cm (4-inch) knife width, thereby increasing throughput and shred size for products such as Type B TDA. Some primary shredders use unique designs with knife spacing as large as 15 cm (6 inches), such as the shredder shown in Exhibit 6-3. In some cases, knife width varies within the machine so that larger knives can be re-sharpened and inserted into a narrower slot, thereby prolonging knife life. Since hook shear knives are removed from the shaft for maintenance, different knife and spacer configurations can be installed during routine maintenance. The rotor assemblies on detachable knife shredders are fixed during initial assembly and are not changeable without replacing the rotors, but different size knives are commonly used in a single shredder or in multiple shredders (if more than one is used) to maximize knife life.

Exhibit 6-3. Tire shedder with 6-inch spaced knives
Photo courtesy of Barclay Roto-Shred Inc., Stockton, CA

Knife Tolerance/Maintenance Requirements – The tolerance between knives is generally 3 to 5 mils (a unit of measure equal to one thousandth of an inch or 0.0254 millimeters) initially to shear the reinforcing wire in tires. As the knives wear, tolerance increases and the reinforcing wire is drawn through the space rather than sheared. Progressively longer extensions of wire therefore occur outside the rubber chip on the resulting product. Extended wire can make the product unsalable to some markets. In addition, failure to cut cleanly creates lateral stresses that can lead to shaft scoring, shaft and bearing failure, and other expensive repairs. Failure to maintain knife sharpness is a short-term savings that seriously increases the cost of long-term machine maintenance.

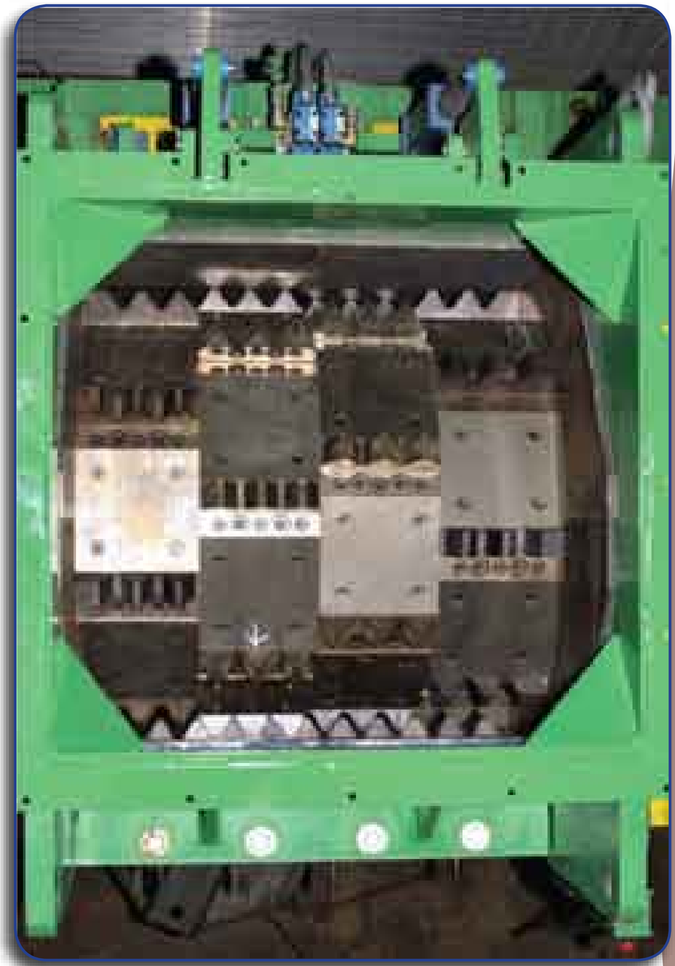
Knife Life – Knife life depends on many variables, especially product size and contamination. Shredding to small tire piece increases wear by requiring more recycle (passes through the shredder) and more cuts. Contamination with other materials can be abrasive, and larger materials can seriously damage shredders. Knives generally last three to five times longer on detachable knife shredders because of the metallurgy, but take two to four times longer to replace when replacement is necessary. Either type can be used on larger shreds, but detachable knives are generally used on nominal 2.5 cm (1-inch) shred such as TDF.

Shaft Considerations – Shafts experience high stress as tires are drawn through the opposing rotors. Shaft design, size, and heat treatment control the shredder's ability to process both passenger and truck tires reliably for extended periods. Undersized shafts in smaller, inexpensive machines may deflect during operation, decreasing knife life and causing fatigue failure. Improper shaft heat treatment during manufacture will also lead to premature stress failure. Shafts 10 cm (4 inches) or smaller will handle only passenger tires and generally indicate minimal shredder construction with limited life. A "bargain" shredder is generally not a long-term bargain.

Wear Points – Shredders experience wear at all points in contact with tires, shreds, or liberated reinforcing wire. Good units have readily replaceable wear plates or thick hard facing in exposed areas and protect shaft bearings from exposure to liberated wire.

Liberation

After the tire has been shredded, higher-speed machines are commonly used to liberate reinforcing wire and fabric while producing 2.5 cm (1 inch) and smaller particle sizes. These machines have staggered knives bolted onto one large central rotor. An internal view of a Columbus McKinnon (CM) Liberator is shown in the photo. Major manufacturers of demonstrated high-volume machines include the Columbus McKinnon Liberator, Eldon Heavy Rasper, and Granutech-Saturn Grizzly. Traditional granulators with more than three veins can also be used in lower-volume installations or for subsequent size reduction. The rotor knives drag shreds through the space between the rotor and hit bars or screens located around the casing. Once liberated, steel is captured by cross-belt and end pulley magnets, and fluff is removed by vibration tables or aspiration.



Internal view of CM Liberator
Photo courtesy of Columbus McKinnon Corp.

These units operate with larger tolerance because the objective is to tear the wire and rubber, not to cut them cleanly. Screens set up around the perimeter control product size by allowing small particles to escape while larger ones continue to be reprocessed. The product has a broad range of sizes, requiring subsequent screening to narrow the product size range. These machines are extremely maintenance intensive, requiring daily maintenance in high-volume installations. These units are also vulnerable to heat buildup, leading to fires within the machines that can be spread to other areas by burning product or conveyors. Water injection, fluff scrap tire aspiration, and fire control systems are some measures used to control the probability and consequences of fires in these machines.

Classification

Classification is normally used to separate defined chip or ground rubber particle sizes. A trommel is a screened size separator normally used on large shreds such as Type B TDA with the larger pieces returned to the shredder for additional size reduction. Disc screens and tapered slot screens are used during production of smaller pieces, such as 5 cm (2-inch) and 2.5 cm (1-inch) chips. Vibrating screens separate ground rubber by designated mesh size to yield specification products. These classification technologies are all commonly available and recognized.

Processing Economics

Properly constructed scrap tire production facilities are capital-intensive. If they are not capital-intensive initially, they will be by the time the facilities are operating properly or fail. This discussion is intended to provide a generic overview of processing economics and the impact of product size and annual volume on economics. To illustrate volume impact, variable and fixed costs were examined for processing of 250,000, 500,000, and 1,000,000 tires/year. Production of large Type B TDA (see Tire Derived Aggregate Section), nominal 5 cm (2-inch) chips, and nominal 2.5 cm (1-inch) chips were examined to illustrate the impact of piece size. The basis for the capital and operating costs for these scenarios are provided in Appendix G, along with discussion of normal site requirements such as land, paving, building, fencing, and other considerations. Approximate capital and operating costs are provided for each of the product sizes. All costs were based on U.S. experience, and then converted into equivalent conditions in Mexico. However, economics can vary widely and should be adjusted to reflect local conditions before any business or investment plans are made.

Processing economics are extremely volume sensitive. The impact of differing volumes can be illustrated by comparing the capital and operating costs for three processing rates of a facility producing a Type B TDA. Based on the capacity of durable equipment, all three volumes can be produced in 1 shift/day, 5 days/week. Each facility is unique in its productivity, system equipment, layout, labor costs, utility rates, and product mix, and each operation will have different economics. Therefore, the following projections are intended only to provide a basis for volume comparison.

A tire processing facility has the same basic components regardless of production capacity. Larger plants may have more components in series or parallel to increase total capacity. Smaller plants that choose to have smaller equipment have historically been unsuccessful. Equipment selection is dictated by tire construction and strength, so small equipment may not be durable even at low volume.

Approximate variable cost projections for each of these processing rates are provided in Appendix H. Major cost components include labor, power, maintenance, and wire disposal (if necessary). Projected labor costs include applicable taxes and benefits and can vary widely based on location. It should be noted that qualified on-site supervisors capable of identifying and implementing proper operational and maintenance procedures are a critical part of a successful operation, and proper training for this role is essential. Scrap tire processing requires manual labor and monitoring positions regardless of processing volume, so labor is volume sensitive.

Power costs are also subject to wide variation depending on a utility's rate basis, and motors do no generally operate at full capacity. Some utilities establish charge rates based on maximum demand during a limited period. These maximum demand rates can lead to similar monthly power costs for low- or high-volume facilities if steps are not taken to control maximum power demand. Staggered, soft starts on large motors can reduce maximum power draw significantly. Operating during off-peak hours can also reduce power costs.

Maintenance costs depend on specific machinery and operating conditions. However, knife life is generally shorter than is projected by the manufacturer. In addition, deferring necessary knife replacement normally results in accelerated deterioration of other components, including shafts, bearings, and the cutting box. Equipment requires periodic major maintenance, but this cost is often not recognized during initial operation. It cannot be ignored when the machine breaks down and requires substantial rebuilding, however. Therefore, projected maintenance costs are two to three times higher than estimated by the manufacturer to reflect operating realities such as contamination and periodic major maintenance items. Bead wire is not recovered and recycled in these projections, but disposal costs can be significant if chips that contain bead wire cannot be used.

As illustrated in Appendix H, total variable cost per tire decreases from $0.47/tire to $0.21/tire as a function of increasing volume. Volume sensitivity results from relatively fixed labor costs for minimal staffing, even though some other major costs are directly proportional to throughput.

Operators sometimes focus their attention on variable costs and fail to recognize the impact of fixed costs. However, fixed costs are economically significant and show considerably greater variation in volume since administrative and capital charges are not directly proportional to volume. Comparative fixed costs are also provided in Appendix H, including administration, capital, and general components.

Administrative staffing varies with tire collection and product marketing requirements. Administrative savings can be self-defeating if inadequate time or resources is devoted to critical marketing or management functions. Professional services such as legal, accounting, and technical assistance are often ignored, resulting in higher ultimate cost associated with inefficient use of management time and resources. Equipment depreciation is also a real cost in tire processing. Even with proper maintenance, equipment simply reaches a point where replacement is less expensive than continued repair and downtime. Likewise, insurance and property taxes can be significant. As a result, fixed costs per tire are extremely volume sensitive, falling from $0.84/tire to $0.26/tire with increasing volume. Fixed costs show even greater variation if interest expenses associated with borrowed capital are included.

Total fixed and variable processing costs can decline from $2.31/tire to $0.71/tire with increasing volume (including a 25 percent annual return on investment). Combined revenue from tipping fees and product sales must equal or exceed total processing costs for a facility to remain economically viable on a long-term basis. As a result of this volume sensitivity, a small-volume producer would probably be unprofitable. A comparatively high-volume regional manufacturer should prove to be an economically viable alternative, especially in major population centers.

Similar costs were calculated for facilities making 5-cm (2-inch) and 2.5-cm (1-inch) chips to illustrate the impact of particle size. These costs are provided in Appendix H. Total costs for 5-cm (2-inch) chips decrease from $3.18/tire to $1.00/ tire at higher volumes, which is significantly higher than for Type B TDA at comparable volume. The cost range for nominal 2.5-cm (1-inch) chips is $3.46/tire to $1.15/ tire, higher than for 5-cm (2-inch) chips.

This volume and size impact is summarized in the table below. With production of Type B TDA at 1 million tires/year as the baseline, other total costs have been ratioed as percentage increased from this base. The data clearly indicate that a careful evaluation of projected operating volumes and products is required before the investment is made.

Table 6-1. Volume and Size Impacts to Total Cost

PRODUCT	VOLUME (tires/year)		
	250,000	500,000	1,000,000
Type B TDA	+225%	+70%	Baseline
Nominal 2-inch chip	+348%	+138%	+40%
Nominal 1-inch chip	+387%	+166%	+62%

ECONOMIC SENSITIVITY

A detailed analysis of ground rubber economics is not presented because short-term development of adequate markets in Mexico is unlikely, and ground rubber facilities have even higher volume sensitivity because of the higher capital and operating costs. However, a schematic representation of a ground rubber facility is provided in Exhibit 6-4.

A turn-key ground rubber facility capable of producing 5,000 pounds of ground rubber per day was recently quoted at more than $4 million plus land, building, concrete, electrical supply, and related costs. Total costs would exceed $5 million, or more than $1,000 per pound per day. Capital costs of this magnitude are unlikely to be sustainable at low volume as markets slowly develop. The best opportunity for success would involve adding a machine such as a Liberator, Rasper or Grizzly (with associated classification equipment) to a centralized tire shredding facility. This machine could produce product sizes ranging from mulch to synthetic turf infill in varying quantities. Ratios could be altered by changing screens on the granulator to produce finer material or by addition of a cracker mill to further reduce particle size for finer ground rubber. This material could be used to develop markets if similar materials cannot be purchased less expensively from existing producers in the United States or Europe. This equipment generates significant quantities of liberated reinforcing wire and fabric that must be separated from the rubber. Wire can be reused as a steel feedstock in foundries, but may require blending

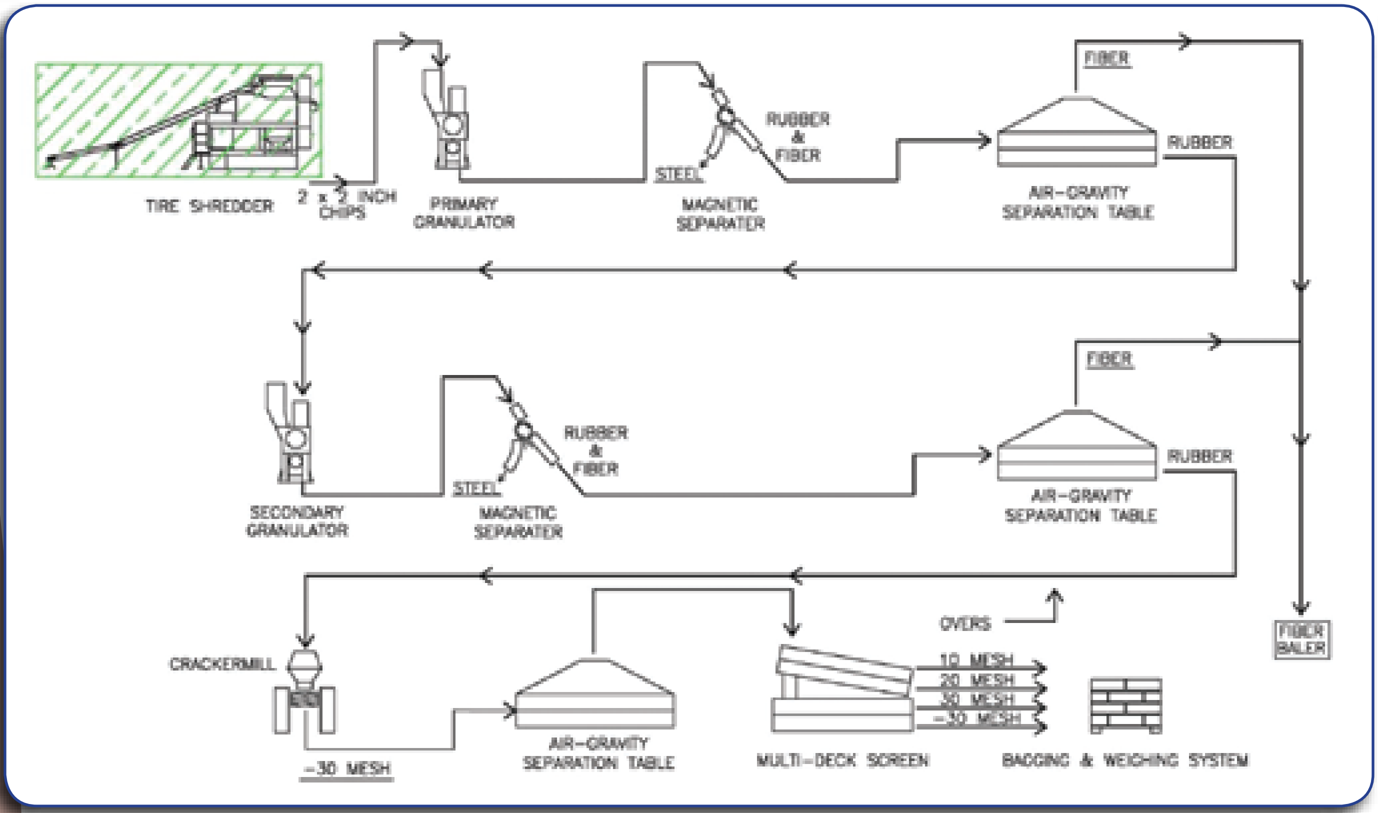


Exhibit 6-4. Schematic representation
Source: Columbus McKinnon Corporation

with other feedstock or additional processing to reduce rubber contamination or increase its density. The fabric has limited use as a fuel in cement kilns.

SUMMARY

There are many critical components to the successful implementation of a scrap tire management program. Transportation, tire processing, and market potential are three key factors to consider before implementation. Attention to travel distance, volume and frequency of tire collection, loading techniques, and other aspects can help lead to optimal equipment usage and ultimately achieving an economically sound transportation and tire collection program. Additional thorough understanding of the markets, specifications, pricing, and raw material availability for scrap tire processing can prevent letdowns similar to those seen by prior U.S. processors. The success or failure of new and established programs may also be affected by variables such maintenance, personnel, and administrative duties. Experiences of attempted and established programs in the U.S. can serve as valuable lessons learned for potential programs in Mexico.

CHAPTER 7

Conclusion

Scrap tires are a concern for Mexico, with many scrap tire piles concentrated throughout the U.S – Mexico border region. In addition to the numerous environmental and public health concerns that scrap tire piles can raise in communities, they represent a vastly underutilized market for recycled materials.

This scrap tire resource handbook has presented a variety of viable options for the Mexico border region to take advantage of the scrap tire market. Many U.S. states have been able to successfully clean up scrap tire stockpiles, establish programs to halt the formation of future stockpiles, and mitigate the risks posed to human health and the environment posed by tire stockpiles. This handbook reflects the lessons learned in the process of reaching that success.

This handbook highlights the important considerations for establishing and implementing scrap tire abatement and reuse programs. The following key points will aid in the successful implementation of a scrap tire program:

- Promote and identify markets for scrap tires in or around your community.
- Identify a specific market before choosing a particular scrap tire application, such as crumb rubber or tire shreds.
- The use of tire-derived fuel is a beneficial use of scrap tires as long as there are adequate emission controls on the facility that will use scrap tires as fuel.
- The use of scrap tires in civil engineering applications, in some cases, can be a viable alternative to tire-derived fuel, as highlighted in Chapter 5.
- The economic analysis as described in Chapter 6 is critical to scrap tire program success; transportation, tire processing, and market potential are three key economic factors to consider before implementation.
- It is important to involve an experienced scrap tire expert before making a decision to spend money on pyrolysis, gasification, or thermal induction. While these methods are evolving and may become economically viable in the future, they have not proven economically viable thus far.

Additional information, lessons learned, and case-studies from established programs can be found throughout the handbook; links for further reading are supplied when available and will provide valuable information to local government or private industry ready to explore the scrap tire market.

Scrap tire pile near Ciudad Juarez

GLOSSARY

Abatement: The removal of scrap tires from stock piles or other sites with accumulations of whole or shredded scrap tires.

Abrasion: Wearing away by scraping or rubbing. The progressive wearing away of a tire tread in service.

Accelerant: A substance used to speed up the combustion process.

Accelerator: A substance added in small amounts to uncured rubber compounds prior to the vulcanization process to reduce the time required for vulcanization.

Aggregate: Rock or stone of uniform size or a range of sizes from either naturally occurring deposits or from artificially prepared materials. Other materials such as scrap tire shreds can be used in some cases to replace rock or stone.

Course Aggregate: Aggregate predominately retained on number 4 sieve.

Fine Aggregate: Aggregate passing the 3/8th inch sieve and almost entirely passing the number 4 sieve.

Aging: Deterioration of physical and chemical properties by oxidation over a period of time.

Air Pressure: Force exerted by air within the tire; expressed in pounds per square inch, kilopascals or bars.

Air Void: A space in cement paste, mortar, or concrete filled with air.

Alignment: Adjustment of steering and suspension components to facilitate the most efficient operation of all tire and wheel assemblies as related to vehicle control and tire wear.

All Season Radial: A highway tire designed to meet the weather conditions in all seasons of the year and which meet the U.S. Rubber Manufacturers Association definition of a mud and snow tire.

Altered Tire: A scrap tire which has been modified so that it is no longer capable of holding or retaining air, water or being used on a vehicle.

Alternative Means of Protection: An application to use another form of fire protection over what is required by code or regulation.

Ambient Rubber: Rubber processed without freezing.

Ambient Temperature: Temperature of the media surrounding an object; such as the air temperature in which a tire may be running or is being processed (shredding); typically this is the same temperature of the room or the outside area being used to process the tire.

Anaerobic: The ability for microorganisms to live without the presence of oxygen.

Annual Take-Off: The number of scrap tires generated in any calendar year.

Antioxidant: A chemical used to retard deterioration specifically caused by oxygen.

Antiozonant: A chemical compounding material used specifically to retard deterioration caused by the ozone.

Arm-Dump Railcar: A type of railcar used to transport materials.

Arson: The criminal act of burning property.

Asphalt: A dark brown to black cement-like material in which the predominant constituents are bitumens which occur in nature or are obtained from petroleum processing.

Asphalt Binder: The asphalt-cement portion of an asphaltic concrete mixture.

Asphalt Cement: A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements.

Asphalt Concrete: An aggregate mixture with an asphalt cement binder.

Asphalt Rubber: A blend of asphalt cement, ground tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot mix asphalt cement sufficiently to cause swelling of the rubber particles.

Asphalt Rubber Chip Seal: A thin layer of crumb rubber-modified asphalt used to bind an aggregate wearing course to a roadway surface.

Aspiration: The uptake by suction of tire fluff or other light materials into tire processing machinery.

ASTM D11 Rubber Committee: A committee formed by the American Society for Testing and Materials (ASTM). The scope of the committee is the formulation of the test methods, definitions, specifications, practices, and classifications pertaining to rubber, rubber products, and systems and services appropriate to rubber technology.

Backing: The material used on the application side of tread rubber, repair units, and tube patches to ensure cleanliness, tackiness and ease in shipping and storing.

Bagel Cut: Cutting the tire in half along its circumference.

Baghouse: Designed to handle heavy dust loads, a dust collector system consists of a blower, dust filter, a filter-cleaning system, and a dust receptacle or dust removal system. It is distinguished from air cleaners which use disposable filters to remove dust.

Baling: A method of volume reduction whereby tires are compressed into bales.

Balance: The distribution of weight around a tire or tire/wheel assembly. The uniform distribution of weight will produce a balanced tire.

Base Course: A sub-layer material of an asphalt road to provide a foundation to support the top layer(s) of the pavement. Generally consists of a specific type of construction aggregate that is a middle surface below the sub-grade and above the sub-base underneath an asphalt road or that is placed directly on top of the undisturbed soil.

Batch Plant: A manufacturing facility for producing bituminous paving mixtures that proportions the aggregate constituents into the mix by weighted batches and adds bituminous material by either weight or volume.

Barrel Stack: A means of storing tires, where the tires are neatly stacked one upon another.

Bead: The anchoring part of the tire which is shaped to fit the rim. The bead is constructed of high tensile steel wires wrapped by the plies.

Bead Separation: Loss of adhesion between the components in the bead area of a tire.

Bead-to-Bead Measurement: A measurement from the bead across the crown to the opposite bead, taken after buffing to ensure selection of the correct matrix size in which to cure a retread.

Bead-to-Bead Retreading: A retreading process which includes veneering of the sidewall from the shoulder to the bead.

Bead Wire: A high tensile steel wire, surrounded by rubber, which forms the bead of a tire that provides a firm contact to the rim.

Bear Claw: The rough-edged bead wire sticking out from a shredded tire.

Belt: An assembly of rubber coated fabric or wire used to reinforce a tire's tread area. In radial tires, it also constrains the outside diameter against inflation pressure and centrifugal force.

Belt Wire: A brass plated high tensile steel wire cord used in steel belts.

Bias Ply Tires: A tire built with two or more casing plies which cross each other in the crown at an angle of 30 to 45 degrees to the tread centerline.

Binder: A component material which when mixed with water or other liquid hardens to hold together aggregate particles into a rigid heterogeneous mass.

Bitumen: A class of black or dark-colored cement-like substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalt, tars, pitches and asphaltites are typical.

Bituminous: Materials containing or treated with bitumen.

Bleeding: The autogenous flow of mixing water within, or its emergence from newly placed concrete or mortar caused by the settlement of the solid materials within the mass.

Bleeding A Tire: The practice, not recommended by the tire manufacturers, of letting hot air out of tires under load and after they have been running in order to reduce inflation.

Blowout: Instantaneous rupturing of tire body, causing complete loss of air pressure.

Blue Triangle: A bulge due to a section repair is allowed not to exceed 3/8th of an inch (1 cm) in height. This bulge may sometimes be identified by a blue triangle label in the immediate area.

Body: Tire structure not including the tread (also refer to casing and carcass).

Bond: A type of insurance agreement which provides a financial guarantee or pledge that an undertaking will be completed. Or a guarantee from financial loss caused by the act, or default, of a third person. Fixed sums are paid annually until bond maturity then repayment of principle is expected.

Borehole: A deep, narrow hole bored or drilled in the earth to extract a liquid, for building construction or to collect samples for analysis.

Brand Number: A number branded into one or both sidewalls of a tire by the customer for identification purposes.

Break: A rupture or opening in the tire structure.

BTU: British Thermal Unit; defined as the amount of energy required to heat one pound of water one degree Fahrenheit.

Buckle: The wrinkling or abnormal deflection of the sidewall when the tire is under- inflated, over-loaded or under severe strain; the abnormal deflection in the belts as a result of improper retreading.

Buffer: The equipment used to remove the old tread from the tire that is to be retreaded. A powerful rotary rasp that provides a rough, clean, even surface to which new rubber readily adheres. A flexible shaft buffer is used for preparing a small area for repairing.

Buffing: The process of removing worn/used tread from a tire to be retreaded. A rotating rasp that provides a rough, clean, even surface to which new rubber readily adheres. A flexible shaft buffer used for preparing a small area for repairing. Buffings can also be produced during the manufacturing of a tire by grinding to expose white rubber on a finished tire, creating a white sidewall or raised white letters on the tire.

Buffing Dust: See Buffings.

Buffing Rubber: A term used by ASTM D11 Rubber Committee. Particulate rubber produced as a byproduct of the buffing operation in the carcass preparation stage of tire retreading. It is characterized by a wide range of particulate sizes which are predominately elongated or acicular in shape. (also refer to Particulate Rubber). The appearance of the unique shape of the particles of this material is only apparent in finished goods or products which contain particles having a dimension greater in size than (30 mesh).

Buffings: Vulcanized rubber usually obtained from a worn/used tire in the process of removing the old tread in preparation for retreading. This material is typically used in molded rubber products. Also referred to as buffing dust.

Build-Up: The application of retread or repair rubber.

Bulge: A protrusion or raised area, usually in the tire sidewall.

Burn-It: A fire fighting strategy that would allow for the free-burn of a tire pile fire.

Bury-It: A fire fighting strategy that suggests burying a tire pile with soil, sand, gravel, cement dust or other cover material.

Butyl Rubber: A general purpose synthetic elastomer (rubber) produced by copolymerizing isobutylene with a small amount of isoprene. Butyl rubber has a low permeability to gases. Its impermeability to air is 70 percent better than natural rubber; for this reason is superior for liner tubes and for tubeless tire inner liners.

Calcining: Heating a substance to a high temperature, but below its melting point, to bring about thermal decomposition.

Carbon Black: A material used in tires that provides strength to rubber compounds. This material consists essentially of elemental carbon in the form of near spherical colloidal particles and aggregates. Carbon black is obtained by partial combustion or thermal decomposition of hydrocarbons.

Carcass: The basic tire structure excluding the tread (also referred to as a Casing).

Casing: The main body of the tire but not including the tread or sidewall rubber.

Casing Jockey: An individual or an independent business that collects used or scrap tires from tire vendors or automotive disassembly facilities and transports them to another location. (also refer to Tire Jockey).

Catalyst: A chemical that in small quantities speeds up the reaction of a resinous material but is not itself a necessary part of the final product.

Celsius: A temperature scale in which zero (0) degrees is the freezing point and 100 degrees is the boiling point (formerly called centigrade).

Change-Over: The removal of tires on cars or trucks and substitution of a different size or type of tire.

Char: The solid residue remaining after pyrolysis of a tire and after removal of steel, fiber or other support material.

Checking: Minute cracking in the surface of rubber caused by aging and oxidation.

Chemical Cure: Vulcanization at room temperature or above activated by chemical agents without the application of heat from an outside source.

Chip-Chunk: Refer to Chunking.

Chip Seal: A thin layer of sprayed asphalt, with or without rubber, and subsequent aggregate placement used to prolong pavement surface life.

Chipped Tire: Pieces of scrap tires that have a basic geometrical shape and generally smaller than 6 inches by 8 inches in size (also refer to Tire Chip).

Chipping: Refer to Chunking.

Chopped Tire: A scrap tire that is cut into relatively large pieces of unspecified dimensions.

Chunking: The loss of either small or substantial pieces of the tread caused by the cutting or breaking action of rough terrain or poor highway surfaces. This is normally associated with highway tires when incorrectly used off the road. Also referred to as chipping or chip-chunk.

Civil Engineering Application: The use of scrap tires in lieu of natural occurring materials (i.e., rock, sand, dirt, gravel) in construction.

Clam Shell: Refer to Bagel Cut.

Classifier: Equipment designed to separate oversized tire shreds from the desired size.

Combustion: The chemical reaction of a material through rapid oxidation with the evolution of heat and light.

Commercial Tires: Truck and industrial tires.

Compacted Tire: Refer to Baling.

Compound: A mixture of blending chemicals specifically tailored to the needs of the specific components of the tire.

Compressible inclusion: Used in applications where a strong yet lightweight material is required to reduce stresses on structural elements.

Concrete: A composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregate; in hydraulic cement concrete, the binder is formed from a mixture of hydraulic cement and water.

Conflagration: A large, uncontrollable fire.

Containment: A fire fighting operation that prevents the further spread of a fire.

Continuous Mix Plant: A manufacturing facility for producing bituminous paving mixtures that proportions the aggregate and bituminous constituents into the mix by a continuous volumetric proportioning system without definite batch intervals.

Control: The overall fire fighting operation of confinement and suppression. A fire is under control when the advance of the fire has been halted.

Converted Tire: A scrap tire which has been processed into a usable commodity other than a tire.

Copolymer: A polymer formed from two or more types of monomers.

Cords: The strands of wire or fabric that form the plies and belts in a tire.

Crambient Rubber: A mixture of ambient and cryogenic rubbers. The ambient being less dense than the cryogenic, the ambient tends to works its way to the top, resulting in inconsistent shock absorption.

Cracker Mill: A machine designed to size reduce scrap tires by passing the scrap material through rotating corrugated steel drums with angular grooves.

Cracking: A sharp break or fissure in the surface of rubber particles that develops upon exposure to light, heat, ozone or repeated bending or stretching.

Crazing: A surface effect on rubber or plastic articles characterized by many minute cracks.

Cross Linking: When chemical bonds set up between molecular chains, the material is said to be cross linked. Once cross linked, a material cannot be reprocessed.

CRREL: Cold Regions Research and Engineering Laboratory. A U.S. Army Corps of Engineers testing laboratory. CRREL has been working on a Chunk Rubber Asphalt Concrete mix, which is designed to enhance ice-disbonding characteristics of several asphalt paving materials.

Crude Rubber: Natural, unprocessed rubber.

Crumb Rubber: (1) A coagulated and dried natural latex rubber. (2) Fine particles of vulcanized rubber resulting from mechanical or cryogenic size reduction of scrap tires or other rubber products.

Crumb Rubber Modified Asphalt Concrete (CRMAC): A general term used to identify a group of processes which incorporate crumb rubber modifiers into asphalt paving materials.

Crumb Rubber Modified Asphalt Hot Mix Asphalt: Refer to Crumb Rubber Modified Asphalt Concrete.

Crumb Rubber Modifier: A general term used by the U.S. Federal Highway Administration to identify a group of processes and concepts which incorporate scrap tire rubber into asphalt paving materials.

Crushed Gravel: The product resulting from the artificial crushing of gravel with substantially all fragments having at least one face resulting from fracture.

Crushed Stone: The product resulting from the artificial crushing of rocks, boulders, or large cobblestones, substantially all faces of which have resulted from the crushing operation.

Cryogenics: A crumb rubber modifier production process in which scrap tire rubber is frozen using liquid nitrogen or commercial refrigeration methods to embrittle the rubber. In the cryogenic process, the embrittled rubber is crushed in a hammermill to the desired particle size.

Cure: To vulcanize; also time, temperature and pressure conditions used to vulcanize rubber.

Cured-On Tires: Solid industrial tires vulcanized directly to the steel wheel on which they run. Also called Molded-On Tires.

Curing: Process of heating or otherwise treating a rubber or plastic compound to convert it from a thermoplastic or fluid material into the solid, relatively heat resistant state desired in commercial products. When heating is employed, the process is also called vulcanization.

Debeading: Process of removing the heavy bead reinforcing wire around the rim of the tire. Removal of the bead wire prior to shredding allows for a cleaner end product and provides less wear on the moving parts of the shredder.

Deflection: The distortion of the tire from its normal shape.

Dense Graded Aggregate: An aggregate that has a particle size distribution such that when it is compacted, the resulting voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, are relatively small.

Density: A term that denotes the weight per unit of volume of a substance. The density of any substance can be obtained by dividing the weight of the substance by its volume.

Depolymerization: The process of reducing the chain length of polymers by breaking their chemical bonds.

Devulcanization: A process in which there is substantial regeneration of the rubber compound to its original plastic state, thus permitting the product to be processed, compounded or vulcanized. Combined sulfur is not affected. True devulcanization of vulcanized rubber with regeneration of the original rubber and removal of combined sulfur has not been accomplished. The term is synonymous with reclaiming of vulcanized scrap rubber. It is primarily a depolymerization accompanied by some oxidation.

Dewired: The absence of exposed wire on the perimeter of the tire chips. Belt wire typically remains in the chip, but is embedded in the chip.

Disposal Fee: Refer to Tipping Fee.

Dog Tracking: A condition where the rear wheels of a vehicle do not follow the path of the front wheels.

DOT Number: An identification number molded by the manufacturer into the sidewall of a highway use tire in compliance with federal motor vehicle safety standard requirements set by the U.S. Department of Transportation (USDOT).

Drown-It: A fire fighting strategy that suggests using copious amounts of water on a tire pile fire.

Dry Process: A paving product made with ground rubber as an aggregate component. The rubber is mixed with the aggregate prior to blending in the asphalt cement in quantities ranging up to three percent rubber. This process is also referred to as Rubber Modified Asphalt Concrete (RUMAC).

Duals: The term used to describe a set of two tires and wheels used on each end of an axle.

Due Diligence: Generally, the degree of care, based on information gathering and analysis, which a reasonable person would take to evaluate risks before entering into an agreement or business transaction with another party.

Elasticity: The property of material by how much it tends to return to its original size and shape after removal of the stress which caused its deformation.

Elastomer: A polymeric material which, at room temperature, is capable of recovering substantially in shape and size after removal of a deforming force. This term generally refers to synthetic polymers as opposed to rubber, which generally refers to the natural material.

Electrostatic Precipitation: The process of removing small particles of smoke, dust, oil, etc., from air by passing the air first through an electrically charged screen that gives a charge to the particles, then between two charged plates where the particles are attracted to one surface.

Elongation: A characteristic of rubber which measures the point to which it can be stretched without breaking.

Embrittlement: A rubber compound becoming brittle during low or high temperature exposure or as a result of aging.

End User: (1) The last entity who uses the tire, in whatever form, to make a product or provide a service with economic value for other uses. (2) The facility which utilizes the heat content or other forms of energy from the combustion of scrap tires for energy recovery.

Energy Recovery: A process by which all or part of the tire is utilized as fuel to recover its BTU value. See Tire Derived Fuel (TDF).

Exothermic: A chemical reaction in which heat energy is liberated.

Extender: (1) An inert material added to a compound to increase volume and lower cost (2) An organic material used to augment or replace part of the polymer in a compound.

Extruder: A machine with a driven screw for continuous forming of rubber by forcing it through a die.

Extrusion: Process of mixing, heating, and forcing a raw material through a die to produce a continuous shape.

Fabric: Textile cords used in tire manufacturing.

Face -of a tire: A term commonly used to denote the surface area of the tread of an off- the-road tire.

Fatigue Cracking: Cracks in a road surface resulting from repeated compression by vehicle weight.

Feedstock: A raw material supplied to a machine or processing plant for the industrial manufacture of a product.

FHWA: Federal Highway Administration, a part of the U.S. Department of Transportation.

Filler: A solid compounding material which may be added, usually in finely divided form, in relatively large proportions, to a polymer.

Financial Assurance: A performance bond, letter of credit, cash deposit or other mutually acceptable financial instrument used to guarantee performance.

Fines: (1)Small particles of graded aggregate used in asphalt concrete composition. (2) Small particles of ground rubber that results as a by-product of processing scrap tires into granules.

Fishhooks: Strands of belt or bead wire exposed from a processed scrap tire or an individual piece of belt or bead wire (also refer to Bear Claw).

Flash: Excess rubber squeezed between the edges of mold segments during the curing process.

Flash Point: The lowest temperature at which the vapor of a combustible liquid can be made to ignite momentarily in air.

Fleet Service: The professional rendering of tire maintenance service to the truck operator or other user. Usually includes the periodic inspection of all rolling wheels at the fleet's place of business.

Fluff: The fibrous, non-rubber, non-metal portion of a tire which remains after the scrap tire is processed (i.e., cotton, rayon, polyester, fiberglass or nylon).

Footprint: The impact made by a tire's tread that comes in contact with the ground.

Full Cap: A retread process that includes replacing the shoulder area and the tread area of the tire.

Full Retreading: The process of buffing scrap tires in the following way: across the top of the tread, down over the shoulder to the upper sidewalls, and replacing the tread and/or sidewall rubber. This retread method will give the shoulders a finished appearance similar to that of a new tire.

Gasification: A process that occurs when tires are subjected to a high temperature, low oxygen environment.

Generic Dry Process: A non-patented procedure for incorporating ground rubber into conventional dense or gap graded hot mix asphalt using the dry process.

Geocomposite: The basic philosophy behind geocomposite materials is to combine the best features of different materials in such a way that specific applications are addressed in the optimal manner and at minimum cost. Thus, the benefit/cost ratio is maximized. Such geocomposites will generally be geosynthetic materials, but not always.

Geomembrane: A kind of impermeable geosynthetic material used widely as cut-offs and liners. The physical material properties of geomembranes include thickness, density, water vapor transmission, solvent vapor transmission, and melt flow index.

Geosynthetic: A range of generally polymeric products used to solve civil engineering problems. The term is generally regarded to encompass eight main product categories: geotextiles, geogrids, geonets, geomembranes, geosynthetic clay liners, geofoam, geocells (cellular confinement) and geocomposites.

Geotextile: Permeable fabrics which, when used in association with soil, have the ability to separate, filter, reinforce, protect, or drain. Typically made from polypropylene or polyester.

Granulated Rubber: Particulate rubber composed of mainly non-spherical particles that span a broad range of maximum particle dimension, from below 425um (40 mesh) to 12mm (0.47 in). The key feature of this type of particulate rubber is the fraction of the material in the greater than 2mm (0.08 in) up to 12mm (0.47 in) maximum particle dimension range. A term defined by ASTM D11, Rubber Committee. See Particulate Rubber.

Granulator: A machine that shears apart scrap tire rubber with revolving plates producing ground particles, generally 3/4 inch to 200 mesh (also refer to Granulated Rubber).

Gravel: Course aggregate resulting from the natural disintegration and abrasion of rock or processing of weakly bound conglomerate.

Green Tire: A tire which has not been vulcanized or cured.

Grooves: The channels between the tread ribs of a tire.

Ground Rubber: Particulate rubber composed of mainly non-spherical particles that span a range of maximum particulate dimension, from well below 425um (40 mesh) to 2.032 mm (0.08 in) as a maximum particle dimension. See Particulate Rubber. The smallest reported mesh size for ground rubber is 450 mesh. The term used by ASTM D11 Rubber Committee.

Hair: Wire protruding from the perimeter of a tire chip or shred (also refer to Fish Hook).

Hammermill: A machine that mechanically processes cryogenically frozen scrap tire rubber using rotating impact hammers.

Hauler: A transporter of goods. A person or company whose business it is to transport goods or materials, especially by road.

Heat Build Up: The generation of heat due to hysteresis when rubber is rapidly or continually deformed.

Heavy-Duty Tires: Tires weighing more than 40 pounds, used on trucks, buses and off-the- road vehicles in heavy duty applications.

Horizontal Stress: Normal stress on a vertical plane.

Horsetail: A rough piece of shredded tire with a width of two to four inches, and a length greater than six inches.

Hot Mix Asphalt: A composition consisting primarily of graded aggregate and asphalt cement widely used for paving..

Hydrocarbon: An organic chemical compound containing only the elements carbon and hydrogen.

Hydroplaning (Aquaplaning) of Pneumatic Tires: A phenomenon that occurs when the road contact surface of a pneumatic tire is separated from the road by a fluid, usually water.

Hysteresis: The heat generated by rapid deformation of a vulcanized rubber part. It is the difference between the energy of the deforming stress and the energy of the recovery material.

Incipient: The beginning or early phase of a fire where the heat being generated has not extended to the surrounding materials.

Inflation: The amount of air pressure in a tire.

India Rubber: An early name for natural rubber, as it came from the "Indes".

Injection Molding: A molding operation wherein a rubber compound is heated in the barrel of an extruder and injected into the mold cavity while in a fluid state.

Injury: Any damage caused by a penetrating object, severe scuff or impact.

Innerliner: The layer or layers of rubber laminated to the inside of a tubeless tire to contain the inflation medium.

Jockey: Refer to Casing Jockey or Tire Jockey.

Kilojoules: A metric measurement of the release of energy. One kilojoule/kilogram is equal to 2.33 BTU pound.

Kilopascals (Kpa): Metric unit of measurement for air pressure.

Ko: The coefficient of the pressure that soil exerts in the horizontal plane. This pressure is known as lateral earth pressure. The common applications of Ko are for the design of ground engineering structures to determine the friction on the sides of, for example, retaining walls and tunnels.

Laced Tires: See Lacing.

Lacing: A method of stacking tires which conserves space.

Latex: Milk-like liquid that comes from a rubber tree. Crude rubber is coagulated from latex.

Leachate: A liquid containing soluble material formed when rainwater or another liquid passes downward through soil or other material. Especially a solution containing contaminants picked up through the leaching.

Light-Duty Tires: Tires weighing less than 40 pounds, used on passenger cars and light trucks.

Light Truck Tire: Tires with a rim diameter of 16 to 19.5 inches that are manufactured specifically for light truck use.

Logger Tire: A special tire designed for the logging industry.

Maintenance Mix: A mixture of bituminous material and mineral aggregate applied at ambient temperature for use in patching holes, depressions, and distressed areas in existing pavement.

Managed Site: A tire pile or storage facility where the owner/operator stores or processes scrap tires in compliance with the appropriate regulations.

Matrix: The retreading equipment in which the new tread is cured to the worn casing and where the tread design is formed.

Mesh: A size unit describing the number of openings per inch in a screen. For example, a 50 mesh screen has 50 openings per lineal inch.

Micro Milling: A mechanical process that further reduces ground rubber to very fine particles. The process combines ground rubber and water, forming a slurry which is forced between rotating abrasive discs.

Micron: A unit of length equal to 0.0001 centimeters or 10,000 angstrom units. This term has generally been replaced by the term micrometer.

Millimeter: A metric unit of measurement. 1 millimeter (mm) equals 0.039 inches. 25.4 mm equals 1 inch.

Mixing Tires: Use of different constructions (radial, bias, bias-belted) on a vehicle.

Mold: The heated cavity in which tires are vulcanized. Includes the steam chamber, matrices and adjusting devices.

Mold Cure: A retreading process using uncured tread compounds where the vulcanization takes place in molds.

Monomer: Any molecule that can be united (bound) chemically as part of a unit of a polymer.

Mucker Tire: A flotation type of tire specifically designed for use in soft grounds (also referred to as a Mudder).

Natural Rubber: The material processed from the sap (latex) of Hevca Brasiliensis (rubber trees).

New Tire: A tire which has never been mounted on a rim.

Nominal: A term commonly used to refer to the average size product (chip) that comprises 50 percent or more of the throughput in a scrap tire processing operation. It should be noted that any scrap tire processing operation will also generate products (chips) above and below the "nominal" range of the machine.

Off Road Tire: See OTR

Open Graded Aggregate: An aggregate that has a particle size distribution such that when compacted, the voids between the aggregate particles, expressed as a percentage of the total space occupied by the material, remain relatively large.

Original Equipment Tire: The tires supplied with new vehicles from vehicle manufacturers.

OTR: Off the Road Tire; tire designed primarily for use on unpaved roads or where no roads exist. Built for ruggedness and traction rather than for speed.

Overinflation: The inflation of a tire above the recommended pressure for the load it carries; negative byproducts are rough ride, bruise and impact damage and suspension system damage.

Overloading: The practice of putting more weight on a tire than the tire is designed for or can carry due to low inflation pressure. This is a dangerous practice and is not recommended.

Oversizing: Mounting larger tires than specified on a vehicle to carry heavier loads, to provide increased flotation or to provide other performance changes.

Oxidation: The reaction of oxygen with a rubber product, usually accompanied by a change in feel, appearance of surface or a change, usually adverse, in physical properties.

Ozone: An allotropic form of oxygen. A gas with characteristic odor which is a powerful oxidizing agent. It is present in the atmosphere at low levels and causes cracking in certain types of elastomeric compounds.

Particulate Rubber: Raw, uncured, compounded or vulcanized rubber that has been transformed by means of a mechanical size reduction process into a collection of particles, with or without a coating of a partitioning agent to prevent agglomeration during production, transportation, or storage (Also refer to Buffing Rubber, Granulated Rubber, Ground Rubber, and Powered Rubber). The term used by ASTM D11 Rubber Committee.

Passenger Car Tire: A tire with less than an 18-inch rim diameter for use on cars only.

Passenger Tire Equivalent (PTE): The weight of waste tires or parts of waste tires equivalent to the average weight of one waste passenger tire. The average weight of one waste passenger tire is equal to 20 pounds. For example, one 80 pound truck tire would be 4 PTEs.

Pavement Distress: The physical manifestation of defects or deterioration in a pavement.

Pavement Performance: The ability of a pavement to fulfill its purpose as reflected in the measurable change in conditions over time.

Plantation Rubber: Crude natural rubber obtained from cultivated rubber trees as opposed to wild or uncultivated trees.

Plies: Layers of rubber coated cords.

Pneumatic Tire: A tire which depends on the compressed air it holds to carry the load. It differs from a solid tire in that the tire itself carries the load.

Polybutadiene: A synthetic rubber made by combining many molecules of butadiene into long chain polymers. This rubber is noted for superior tread wear, resiliency and flexing qualities at low temperatures.

Polymer: A macromolecular material formed by the chemical combination of monomers having either the same or different chemical compositions.

Polymer Chain: The chain of elements that form the basis of the structure of a polymer.

Polymerization: A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular mass is a multiple of the original substance. When two or more different monomers are involved, the process is called copolymerization.

Pounds Per Square Inch (PSI): A measure of pressure.

Powdered Rubber: Particulate rubber composed of mainly non-spherical particles that have a maximum particle dimension equal to or below 425um (40 mesh). (Also refer to Particulate Rubber). The term used by ASTM D11 Rubber Committee.

Pre-cure Process: A process of using pre-manufactured treads and vulcanizing these treads to a prepared casing with a thin layer of cushion gum (natural rubber).

Pre-cured Tread: Tread which is vulcanized with the tread configuration molded into it prior to being placed on the buffed casing.

Pre-drying: Drying of a tire in a heated room to remove moisture before retreading.

Pre-Incident Planning: A method of anticipating the response to a particular fire incident and planning the tactics and strategies based on information collected before a fire occurs.

Pressure Build-Up: The increase of air pressure in a tire caused by an increase in the temperature of the contained air.

Preventive Maintenance: Maintenance performed prior to any failure. Designed to lengthen product life, prevent high maintenance costs and to reduce equipment breakdown.

Private Brand: A specialty line of tires or tubes manufactured for and to the specifications of a private buyer who sells these products under its company name.

Processed Tire: A scrap tire which has been altered, converted or size reduced. Methods of processing include; cutting, cryogenic reduction, or shredding.

PTE: See Passenger Tire Equivalent.

Pugmill: A device for mixing the separate hot aggregate and bituminous components into a homogenous bituminous concrete ready for discharge into a delivery system.

Pulverized Rubber: Refer to Ground Rubber.

Pull: The tendency of a vehicle to veer to one side.

Pyrolysis: The process of thermal decomposition in the absence of oxygen. Pyrolyzing scrap tires yields gas, char, oil and steel.

Radial Cracking: Cracking, perpendicular to the bead, usually in or near the sidewall area.

Radial Tire: A tire constructed so that the ply cords extend from bead to bead at a 90 degree angle to the centerline of the tread.

Rate of Cure: The relative time required to reach a predetermined state of vulcanization under specific conditions.

Raw Rubber: Unprocessed, vulcanized elastomer, normally implying the natural product.

Recapping: An improper term for retreading. Often, this term refers to the process of top capping, in which rubber is applied to the tread surface only.

Reclaim: The product from the degradation of rubber by mechanical, thermal, and/or chemical processes, resulting in a depolymerized material.

Reclaimed Asphalt Pavement (RAP): Asphalt pavement or paving mixture removed from its original location for use in recycled asphalt pavement mixtures.

Recovery: The degree to which a rubber product returns to its normal dimensions after being distorted.

Recycle or Recycling: Any process by which worn tires are transformed into new products including retreads, fuel, or ground rubber.

Recycled Asphalt Paving Mixture: A mixture of reclaimed asphalt pavement (RAP) with the inclusion, if required, of asphalt cement, emulsified asphalt, cut back asphalt, recycling agent, mineral aggregate, and mineral filler.

Recycled Rubber Product: Products which contain recycled rubber.

Reinforcement: Any material, usually rubber and fabric, vulcanized to the inside of a tire to add strength to the cord body at an injury.

Reinforcement Repair: Repairs made to the casing when damage has extended through more than 25 percent, but less than 75 percent of the tire body, requiring both hole-filling material and reinforcement units.

Remanufactured Tire: A worn tire that has been properly inspected and/or repaired and has had new rubber applied bead-to-bead to extend its serviceable life (also referred to as a remolded tire).

Repair Materials: Specifically designed materials (repair units, repair gums, cements) used during the repair process of a tire or a tube.

Repaired Tire: A tire that has been injured by cuts, puncture or breaks, and which has been reconditioned to restore its strength for additional service.

Replacement Tire: Any new tire other than those sold as original equipment.

Request for Proposal: The invitation or announcement a funding organization issues for suppliers to submit a bid (proposal) on providing a specific product or service for the funding organization.

Residence Time: The average length of time that a substance spends in a particular system, such as waste tires in cement kiln.

Retail Tire Vendor: A term used to describe retail outlets for tires.

Retreadability: The ability of a tire casing to be retreaded and provide acceptable performance.

Retreaded Tire: A casing to which a new tread rubber, and sometimes shoulder and sidewall rubber, has been vulcanized to extend the usable life of the tire.

Reused Tire: A passenger car tire taken off the rim of a vehicle and placed on the rim of another vehicle without any repair or other form of alteration.

Ribs: The part of a tire tread pattern created by grooves which run circumferentially around the tire.

Rim: The metal support for the tire and tube assembly on the wheel. The beads of a tire are seated on the rim.

Rip-Shear Shredders: A tire shredder designed to reduce a scrap tire to pieces. The size and shape of the tire piece is dependent on the processing action of the shredder (i.e., cutting blades, rotary shear or rip-shear).

RMA: U.S. Rubber Manufacturers Association; The trade association which represents the United States tire manufacturers and the United States based manufacturers of non-tire rubber products.

Road Hazard: Any road or highway condition or obstacle which can damage a tire.

Rough Shred: A piece of a shredded tire that is larger than 2″ x 2″ x 2″, but smaller than 30″ x 2″ x 4″.

Rubber: An elastomer, generally implying natural rubber, but used loosely to mean any elastomer, vulcanized and unvulcanized. By definition, rubber is a material that is capable of recovering from large deformations quickly and forcibly and can be, or already is modified to a state in which it is essentially insoluble in a boiling solvent.

Rubber Latex: Refer to Latex.

Rubber Modified Asphalt: A general term used to identify the incorporation of scrap tire rubber into asphalt paving materials (also refer to Crumb Rubber Modified Asphalt Concrete).

Rubber Modified Asphalt Concrete (RUMAC): A pavement product made with rubber. The rubber acts as an aggregate, and is blended into asphalt cement along with the aggregate in quantities ranging up to three percent rubber. This process is also referred to as the Dry Process.

Rubber Polymer Matrix: An interlaced "screen" comprised of cross-linked, bound rubber macromolecules.

Rubber Reclamation: The process of degradation of the rubber's structure through the use of mechanical, thermal or chemical processes.

Rubberized Asphalt: Refer to Crumb Rubber Modified Asphalt Concrete.

RUMAC: Refer to Rubber Modified Asphalt Concrete.

Run Flat: Tire damage resulting from operating with low or no air pressure, sometimes identified by repetitive liner cracking or discoloration. Also refers to a class of passenger car tires capable of safely operating without air pressure in event of air loss.

Salt and Pepper Granules: Granulated rubber that was made from white wall tires.

SAM: Stress Absorbing Membrane; A rubberized asphalt layer applied over existing pavement to retard fatigue cracking.

SAMI: Stress Absorbing Membrane Interlayers; A rubberized asphalt layer applied over an existing surface before application of a surface asphalt concrete used to retard reflective cracking.

Scrap Pile Analysis: The inspection of tires in a scrap pile of a commercial account to determine causes of tire failures.

Scrap Tire: A tire which can no longer be used for its original purpose due to wear or damage.

Scrap Tire Pile: An accumulation of whole or processed scrap tires.

Scrap Tire Processing: Any method of size reducing whole scrap tires to facilitate recycling, energy recovery or disposal.

Screen: An apparatus for separating sizes of granules.

Secondary Material: Fragments or finished products or leftovers from a manufacturing process which converts a primary material into a commodity of economic value.

Section Repair: Repairs made to the casing when an injury has extended through the tread or sidewall of a tire. The damaged cord is removed and replaced by a repair unit.

Sectioned Tire: A tire that has been cut into at least two parts.

Shoulder: The part of a tire between the tread and the sidewall.

Shred: A cut or torn piece of scrap tire which is usually relatively small and may or may not be uniform.

Shred Sizing: A term which generally refers to the process of cut tire pieces passing through a rated screen opening rather than those which are retained on the screen. Examples of which are:

1" x 1": A size reduced scrap tire with all dimensions one inch maximum.

2" x 2": A size reduced scrap tire, 2" x 2" x 2" maximum.

2" minus: Size reduced scrap tires, the maximum size of any piece has a dimension no larger than one inch, but 95 percent of which is less than X inches in any dimension (i.e., l" minus; 2" minus; 3" minus, etc.).

Shredded Tire: A size reduced scrap tire. The reduction in size was accomplished by a mechanical processing device commonly referred to as a "shredder".

Shredder: A machine used to reduce whole tires to pieces.

Shredded Rubber: Pieces of scrap tires resulting from mechanical processing.

Singulator: A conveyor that receives randomly oriented articles and positions those articles in single file. The conveyor includes skewed rollers for driving articles longitudinally and laterally against a side wall.

Sink Holes: An event that occurs in shredded scrap tire piles that develop as material under the surface is consumed in an internal fire, and the surface caves in.

Sidewall: The side of a tire between the tread shoulder and the rim bead.

Side-Dump Railcar: Type of railcar used for transport of materials. The railcar is tilted on its side to empty it and ensure complete removal of materials.

Sieve: An apparatus for separating sizes of materials (also refer to Screen).

Single Pass Slued: A shredded tire that has been processed with a shear type shredder and the piece has not been classified.

Sipes: Small cuts purposely made in the surface of a tread to improve traction.

Size Reduction: Refers to cutting, shredding or other methods of reducing the size of, usually, a whole scrap tire.

Skid Resistance: The ability of the road surface and the tread to prevent the loss of tire traction.

Skiving: The removal of damaged material prior to malting a repair.

Sludge: Any of various more or less mud-like deposits or mixtures. Heavy, slimy deposit, sediment, or mass, as the waste resulting from various industrial operations.

Slurry: A thin mixture of an insoluble substance, as cement, clay, or coal, with a liquid, as water or oil.

Source Reduction: Any of a series of practices which act to reduce the number of scrap tires generated annually. These practices include, but are not limited to, using longer mileage tires; maintaining proper inflation; rotating tires; balancing tires; maintaining alignment; repairing tires and retreaded tires.

Speed Rating: Maximum speed capabilities of new passenger and light truck tires are indicated by means of a speed symbol.

Specifications: Written requirements for processes, materials or equipment.

Speculative Accumulation: The stockpiling of scrap tires without the benefit of a business or business plan, but with the expectation that a market will be found.

Split Rubber: A process in which tread is stripped from a tire for subsequent processing.

Spontaneous Combustion: A term often used to explain the cause of internal, processed scrap tire fires. This is an inappropriate use of the term. (Refer to Spontaneous Ignition.)

Spontaneous Ignition: Heat generated by a chemical or bacterial action in a combustible material.

Squirrel Foot: Exposed, rough pieces of belt or head wire (also refer to Fish Hooks).

Steel Belt: Rubber coated steel cords that run diagonally under the tread of steel radial tires and extend across the tire approximately the width of the tread. The stiffness of the belts provides good handling, improved tread wear, and penetration resistance.

Steel Belted Radial: A radial tire made with steel belts as opposed to textile belts.

Stockpile: A storage pile of materials which is usually large and gradually accumulated. The material is sometimes accumulated for possible future use.

Structural Plies: Body and belt plies that contribute to casing strength.

Substrate: A supporting material on which something else is formed or constructed.

Sump: A low area into which a liquid drains, for example a pit or reservoir.

Super-Single: Tires commonly found on off-road and dump equipment. They are a very tall, numerically high aspect ratio tires, as opposed to the "highway singles" which tend to have the same overall height as standard single tires.

Supplemental Fuel: A combustible material which displaces a portion of traditional fuel source.

Surcharge: An extra fee or payment. An additional or excessive load or burden.

Surface Treatment: An application of bituminous material followed by a layer of mineral aggregate on a roadway.

Synthetic Rubber: Rubber that is obtained by polymerizing petrochemical based monomers.

Tactics: The method of securing the objectives laid out in a strategy through the use of personnel and equipment to achieve optimum results.

Take-Off Tire: A tire that has been removed from a vehicle's rim. This includes tires that are used, are candidate casings for repair, retreading, and to be scraped.

Tax Map: An official map showing the boundary lines of properties and parcel dimensions for tax purposes.

TDF: Refer to Tire Derived Fuel.

Thermoplastic: A material with the capability (property) of being repeatedly softened by an increase of temperature and hardened by a decrease in temperature.

Thermoset: The capability of maintaining a physical state across a wide range of temperatures.

Thermoset Plastic: A solid macromolecular material which is incapable of continuous inelastic deformation by raising the temperature without chemical decomposition.

Thermosetting: The property of a substance which undergoes a chemical change when heated, whereby a hardened non-thermoplastic product is formed.

Three Dimensional Fire: A fire occurring within a material that has three surfaces. In the case of scrap tire fires, fire would be present on the upper surface, interior section and the bottom of the tire.

Tipping Fee: Amounts charged by a facility operator for disposing of a scrap tire, or other waste, at that facility or landfill (also referred to as Disposal Fee).

Tire: A continuous solid or pneumatic rubber covering encircling the wheel of a vehicle.

Tire and Rim Association Inc.: A U.S. industrial association of tire, rim and wheel manufacturers which provides tire, rim and wheel standards.

Tire Bounty: An amount paid for the collection and retrieval of illegally dumped or stockpiled scrap tires.

Tire Buffings: Refer to Buffings.

Tire Chip: A classified scrap tire that has a basic geometrical shape, which is generally two inches or smaller and has most of the wire removed (also refer to Chipped Tire).

Tire Dealer: A term used to define independent retail tire vendors.

Tire-Derived Fuel (TDF): Whole scrap tires or a uniformly shredded product obtained from whole tires, used as a fuel.

Tire Jockey: An independent business that hauls scrap tires for a fee from retail tire vendors to another location. Also known as a Casing Jockey.

Tire Maintenance: The practice of establishing and ensuring proper air inflation, tire rotation, balancing, and alignment.

Tire Rotation: The repositioning of the tires on a vehicle periodically to extend tire tread life.

Top Retreading: Only the top, or tread area, is buffed away during the retread process and a tread rubber with abrupt shoulders is applied. This type of retreading is usually requested when tires are used in highway service where a special shoulder is not required and when appearance is secondary.

Transformation: The process of incineration, pyrolysis, gasification, chemical and/or biological conversion of a scrap tire.

Tread: That portion of the tire which contacts the road.

Tread Buffing: Refer to Buffings.

Tread Depth: The measurement from the tread surface to the bottom of the grooves.

Tread Depth Gauge: An instrument used to measure the depth of a tire's tread grooves.

Tread Design: The non-skid pattern design on the tread portion of a tire.

Tread Life: The length of service in miles or hours of operation before the tread wears out.

Tread Peels: Refer to Buffings.

Tread Rubber: Compounded, natural or synthetic rubber which is placed on a buffed casing and vulcanized to it to provide a new wearing surface.

Tread Shaving: The shaving of tread from a tire with a blade (usually to half the original tread depth) to reduce tread squirm and tearing in racing applications.

Tread Wear Indicators: Narrow bars of rubber molded at a height of 2/32nds of an inch across the bottom of the tread grooves. When the tread wears down to these bars, the tire should be replaced. The legal limits of a tire is 3/32nd of an inch of tread.

Trommel: A mechanical device that sorts size reduced scrap tires.

Truck Tire: Tires with a rim diameter of 20 inches or larger.

Tubeless: A pneumatic tire that does not require an inner tube for air retention.

Tube-Type: A pneumatic tire that requires an inner tube for air retention.

Two Dimensional Fire: Fires that occur in a flat plane as in flammable liquid or processed scrap tire fires.

Type A TDA: Tire derived aggregate in which pieces are a maximum of 75 mm (3 inches).

Type B TDA: Tire derived aggregate in which pieces range in size from 75 – 300 mm (12 inches).

Undercure: A condition in which complete vulcanization was not achieved.

Underinflation: A condition in which a tire is inflated below the recommended pressure, resulting in sluggish response, greatly increased tread wear, reduced gas mileage and casing failure.

Uniformity: A measure of the tire's ability to run smoothly and vibration free.

Unmanaged Site: A scrap tire pile or facility where tires are stored that are not in compliance with the appropriate regulations or at a dump site where scrap tires are stockpiled with no intention of reuse, recycling or processing.

Used Tire: A tire removed from a vehicle's rim which cannot be legally described as new, but which is structurally intact and has a tread depth greater than the legal limit. This tire can be remounted onto another vehicle's rim without repair.

Valve: A device used to admit, retain, check or exhaust air in a tube or mounted tubeless tire.

Velcro Effect: The interlocking of wire protruding from tire chips.

Venting: An operation in which bias tires are punctured before retreading to guard against trapped air which causes casing separation.

Virgin Material: Raw material, such as crude oil or aggregate taken from a quarry, that has not been previously used in any manufacturing process.

Void: The space between aggregate tire pieces expressed as a percent of the total space occupied by the tire shreds.

Vulcanization: An irreversible process in which the chemical structure of rubber is changed (cross linked with sulfur) to become less plastic (sticky, putty-like) and more elastic (bouncy) (also refer to Curing).

Vulcanized Rubber: The product of vulcanization in which rubber which has been chemically reacted with sulfur and accelerators (or other acceptable materials) under suitable conditions to achieve modified physical properties over a wide range of temperatures.

Vulcanizing Agent: Any material that can produce in rubber the change in physical properties known as vulcanization, such as sulfur, peroxides, polysulfides, etc.

Vulcanizing Cement: A rubber cement used to bond the new rubber to the old tire.

Waste Tire: A tire which is no longer capable of being used for its original purpose, but which has been disposed of in such a manner that it cannot be used for any other purpose.

Weather Checking: Fine cracks in the sidewall surface of a tire caused by oxidation and other atmospheric effects.

Weaving: Refer to Laced Tires.

Wet Bulb Globe Temperature: A composite temperature used to estimate the effect of temperature, humidity, wind speed (wind chill) and solar radiation on humans. It is to determine appropriate exposure levels to high temperatures.

Wet Process: Any method that blends ground rubber with the asphalt cement prior to incorporating the binder in the asphalt paving project.

Wheel Alignment: Adjustment of wheel ends and axles to ensure the proper orientation of the tires to the chassis and to each other. This ensures the vehicle and the tires roll in a straight line.

Whole Tire: A scrap tire that has been removed from a rim, but which has not been processed.

Wild Rubber: Rubber collected from trees growing wild in nature as opposed to trees cultivated on plantations.

Wires: High tensile, brass plated steel wires, coated with a special adhesion-promoting compound that are used as tire reinforcement. Belts of radial tires plies and beads are common uses.

Wobble: A performance irregularity in tire and wheel assemblies characterized by a side to side motion.

Worn Tire: Any tire which has been removed from a vehicle because of wear or damage. Worn tires can be retreaded, repaired or scrapped.

Zipper: Circumferential rupture of sidewall body cables.

APPENDIX A

TDA Material Specifications

TDA, GENERAL

The material shall be made from scrap tires which shall be shredded into the sizes specified herein. They shall be produced by a shearing process. TDA produced by a hammer mill will not be allowed. The TDA shall be free of all contaminants such as oil, grease, gasoline, diesel fuel, etc., that could leach into the groundwater or create a fire hazard. In no case shall the TDA contain the remains of tires that have been subjected to a fire because the heat of a fire may liberate liquid petroleum products from the tire that could create a fire hazard when the shreds are placed in a fill. The TDA shall be free from fragments of wood, wood chips, and other fibrous organic matter. The TDA shall have less than 1 percent (by weight) of metal fragments that are not at least partially encased in rubber. Metal fragments that are partially encased in rubber shall protrude no more than 25 mm (1 inch) from the cut edge of the TDA on 75 percent of the pieces (by weight) and no more than 50 mm (2 inch) on 90 percent of the pieces (by weight). The gradation shall be measured in accordance with C136-05 (also designated AASHTO T-27), "Standard Method for Sieve Analysis of Fine and Coarse Aggregate," except that the minimum sample size shall be 6 to 12 kg (15 to 25 lbs) for Type A TDA and 16 to 23 kg (35 to 50 pounds) for Type B TDA.

TDA, TYPE A

Type A TDA shall have a maximum dimension, measured in any direction, of 203 mm (8 inch). In addition, Type A TDA shall have 100 percent passing the 102 mm (4 inch) square mesh sieve, a minimum of 95 percent passing (by weight) the 75 mm (3 inch) square mesh sieve, a maximum of 50 percent passing (by weight) the 38 mm (1.5 inch) square mesh sieve, and a maximum of 5 percent passing (by weight) the No. 4 sieve.

TDA, TYPE B

A minimum of 90 percent (by weight) shall have a maximum dimension, measured in any direction, of 300 mm (12 inch) and 100 percent shall have a maximum dimension, measured in any direction, of 450 mm (18 inch). At least one side wall shall be severed from the tread of each tire. A minimum of 75 percent (by weight) shall pass the 203 mm (8 inch) square mesh sieve, a maximum of 50 percent (by weight) shall pass the 76 mm (3-inch) square mesh sieve, a maximum of 25 percent (by weight) shall pass the 38 mm (1.5-inch) square mesh sieve, and a maximum of 1 percent (by weight) shall pass the No. 4 sieve (4.75 mm; 0.187 inch).

APPENDIX B

Design Guidelines to Minimize Internal Heating of Tire Shred Fills

(JULY 1997; REVISED 2003)

BACKGROUND

Since 1988 more than 70 tire shred fills with a thickness less than 1 m and an additional ten fills less than 4 m thick have been constructed. In 1995 three tire shred fills with a thickness greater than 8 m experienced a catastrophic internal heating reaction. These unfavorable experiences have curtailed the use of all tire shred fills on highway projects.

Possible causes of the reaction are oxidation of the exposed steel belts and oxidation of the rubber. Microbes may have played a role in both reactions. Although details of the reaction are under study, the following factors are thought to create conditions favorable for oxidation of exposed steel and/or rubber: free access to air; free access to water; retention of heat caused by the high insulating value of tire shreds in combination with a large fill thickness; large amounts of exposed steel belts; smaller tire shred sizes and excessive amounts of granulated rubber particles; and the presence of inorganic and organic nutrients that would enhance microbial action.

The design guidelines given in the following sections were developed to minimize the possibility for heating of tire shred fills by minimizing the conditions favorable for this reaction. As more is learned about the causes of the reaction, it may be possible to ease some of the guidelines. In developing these guidelines, the insulating effect caused by increasing fill thickness and the favorable performance of projects with tire shred fills less than 4 m thick were considered. Thus, design guidelines are less stringent for projects with thinner tire shred layers. The guidelines are divided into two classes: Class I Fills with tire shred layers less than 1 m thick and Class II Fills with tire shred layers in the range of 1 m to 3 m thick. Although there have been no projects with less than 4 m of tire shred fill that have experienced a catastrophic heating reaction, to be conser¬vative, tire shred layers greater than 3 m thick are not recommended.

In addition to the guidelines given below, the designer must choose the maximum tire shred size, thickness of overlying soil cover to address pavement structural concerns, etc., to meet the requirements imposed by the engineering performance of the project. The guidelines are for use in designing tire shred monofills. Design of fills that are mixtures or alternating layers of tire shreds and mineral soil that is free from organic matter should be handled on a case by case basis.

GENERAL GUIDELINES FOR ALL TIRE SHRED FILLS

All tires shall be shredded such that the largest shred is either: (1) no greater than 0.6 m in any direction measured, or (2) no more than one-quarter of the circumference of the tire, whichever is less. At least one sidewall shall be severed from the tire shred.

The tire shreds shall be free of all contaminates such as oil, grease, gasoline, diesel fuel, etc., that could create a fire hazard. In no case shall the tire shreds contain the remains of tires that have been subjected to a fire because the heat of a fire may liberate liquid petroleum products from the tire that could create a fire hazard when the shreds are placed in a fill.

CLASS I FILLS

Material Guidelines

The tire shreds shall have a maximum of 50 percent (by weight) passing the 38-mm sieve and a maximum of 5 percent (by weight) passing the 4.75-mm sieve.

Design Guidelines

No design features are required to minimize heating of Class I Fills.

CLASS II FILLS

Material Guidelines

The tire shreds shall have a maximum of 25 percent (by weight) passing the 38-mm sieve and a maximum of 1 percent (by weight) passing the 4.75-mm sieve.

The tire shreds shall be free from fragments of wood, wood chips, and other fibrous organic matter. The tire shreds shall have less than 1 percent (by weight) of metal fragments which are not at least partially encased in rubber. Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the tire shred on 75 percent of the pieces and no more than 50 mm on 100 percent of the pieces.

Design guidelines. The tire shred fill shall be constructed in such a way that infiltration of water and air is minimized. Moreover, there shall be no direct contact between tire shreds and soil containing organic matter, such as topsoil. One possible way to accomplish this is to cover the top and sides of the fill with a 0.5 m thick layer of compacted mineral soil with a minimum of 30 percent fines. The mineral soil should be free from organic matter and should be separated from the tire shreds with a geotextile. The top of the mineral soil layer should be sloped so that water will drain away from the tire shred fill. Additional fill may be placed on top of the mineral soil layer as needed to meet the overall design of the project. If the project will be paved, it is recommended that the pavement extend to the shoulder of the embankment or that other measures be taken to minimize infiltration at the edge of the pavement.

Use of drainage features located at the bottom of the fill that could provide free access to air should be avoided. This includes, but is not limited to, open graded drainage layers daylighting on the side of the fill and drainage holes in walls. Under some conditions, it may be possible to use a well graded granular soil as a drainage layer. The thickness of the drainage layer at the point where it daylights on the side of the fill should be minimized. For tire shred fills placed against walls, it is recommended that the drainage holes in the wall be covered with well graded granular soil. The granular soil should be separated from the tire shreds with geotextile.

GENERAL GUIDELINES FOR ALL TIRE SHRED FILLS (July 1997; revised 2003)

All tires shall be shredded such that the largest shred is either: (1) no greater than 0.6 m in any direction measured, or (2) no more than one-quarter of the circumference of the tire, whichever is less. At least one sidewall shall be severed from the tire shred.
Tire shreds shall be free of contaminates such as oil, grease, gasoline, diesel fuel, etc., that could create a fire hazard
In no case shall the tire shreds contain the remains of tires that have been subjected to a fire

CLASS I FILLS (< 1 m thick)
Maximum of 50 percent (by weight) passing 38-mm sieve
Maximum of 5 percent (by weight) passing 4.75-mm sieve

CLASS II FILLS (1-3 m thick)
Maximum of 25 percent (by weight) passing 38-mm sieve
Maximum of 50 percent (by weight) passing 50-mm sieve
Maximum of 1 percent (by weight) passing 4.75-mm sieve
Tire shreds shall be free from fragments of wood, wood chips, and other fibrous organic matter
The tire shreds shall have less than 1 percent (by weight) of metal fragments that are not at least partially encased in rubber
Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the tire shred on 75 percent of the pieces by weight and no more than 50 mm on 90 percent of the pieces by weight
Infiltration of water and air into the tire shred fill shall be minimized
No direct contact between tire shreds and soil containing organic matter, such as topsoil
Tire shreds should be separated from the surrounding soil with a geotextile
Use of drainage features located at the bottom of the fill that could provide free access to air should be avoided

APPENDIX C

Engineering Properties of TDA

Selected engineering properties of tire derived aggregate (TDA) are presented in this appendix. This information includes gradation, compacted unit weight, compressibility, time-dependent settlement, and shear strength.

GRADATION

Large pieces are desirable when the TDA zone is more than 1 m (3.3 feet) thick because they are less susceptible to self-heating (as discussed in Appendix B). However, when the TDA contain a significant number of pieces larger than 300 mm (12 inches), they tend to be difficult to spread in a uniform lift thickness. Thus, a typical specification requires that a minimum of 90 percent (by weight) of the TDA have a maximum dimension, measured in any direction, of less than 300 mm (12 inches) and that 100 percent of the TDA have a maximum dimension less than 450 mm (18 inches). Moreover, at least 75 percent (by weight) must pass a 200-mm (8-inch) sieve and at least one sidewall must be severed from the tread of each tire. To minimize the quantity of small pieces, which can be susceptible to self-heating, the specifications require that no more than 50 percent (by weight) pass the 75-mm (3-inch) sieve, 25 percent (by weight) pass the 38-mm (1.5-inch) sieve, and no more than 1 percent (by weight) pass the No. 4 (4.75-mm) sieve. Pieces of this size are commonly referred to as Type B TDA. When samples are collected for gradation analysis, they should be collected directly from the discharge conveyor of the processing machine. This procedure ensures that the minus No. 4 fraction will be representative, which is not the case when samples are collected by shoveling pieces from a stockpile. TDA that meets the size requirements given above generally have a uniform gradation. Typical results are shown in Exhibit C-1.

COMPACTED UNIT WEIGHT

The compacted unit weight of TDA has been investigated in the laboratory for pieces up to 75 mm (3 inches). These tests were generally done with 254-mm (10-inches) or 305-mm (12-inches) inside

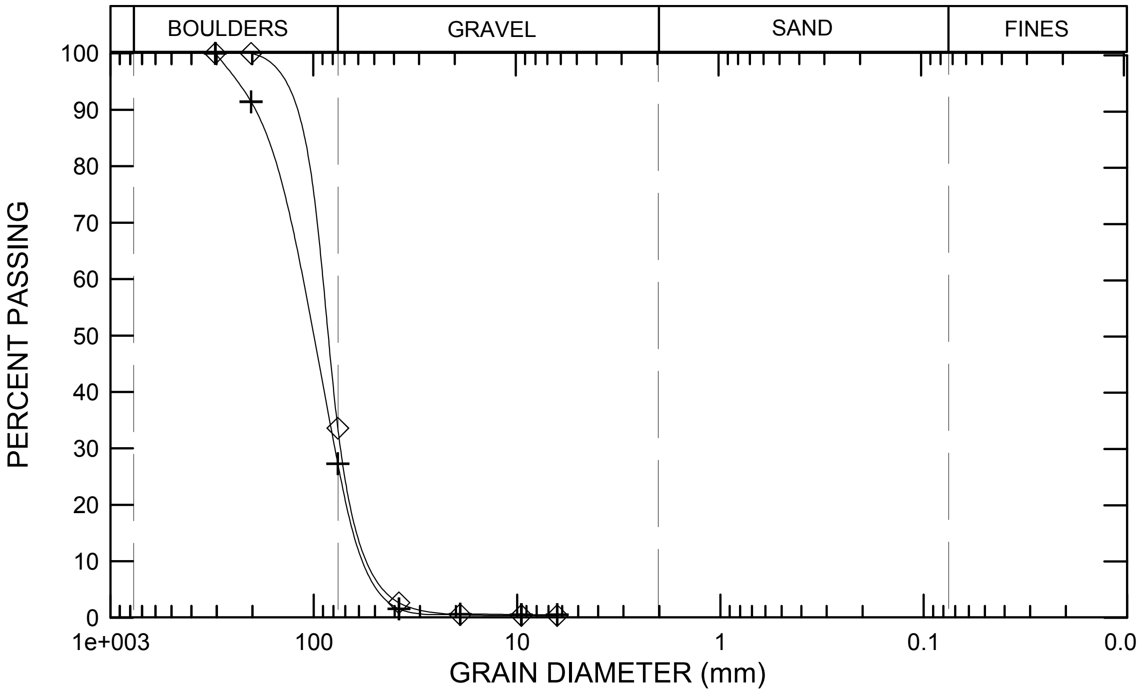


Exhibit C-1. Gradation of Type B TDA used as lightweight fill for Portland Jetport Interchange

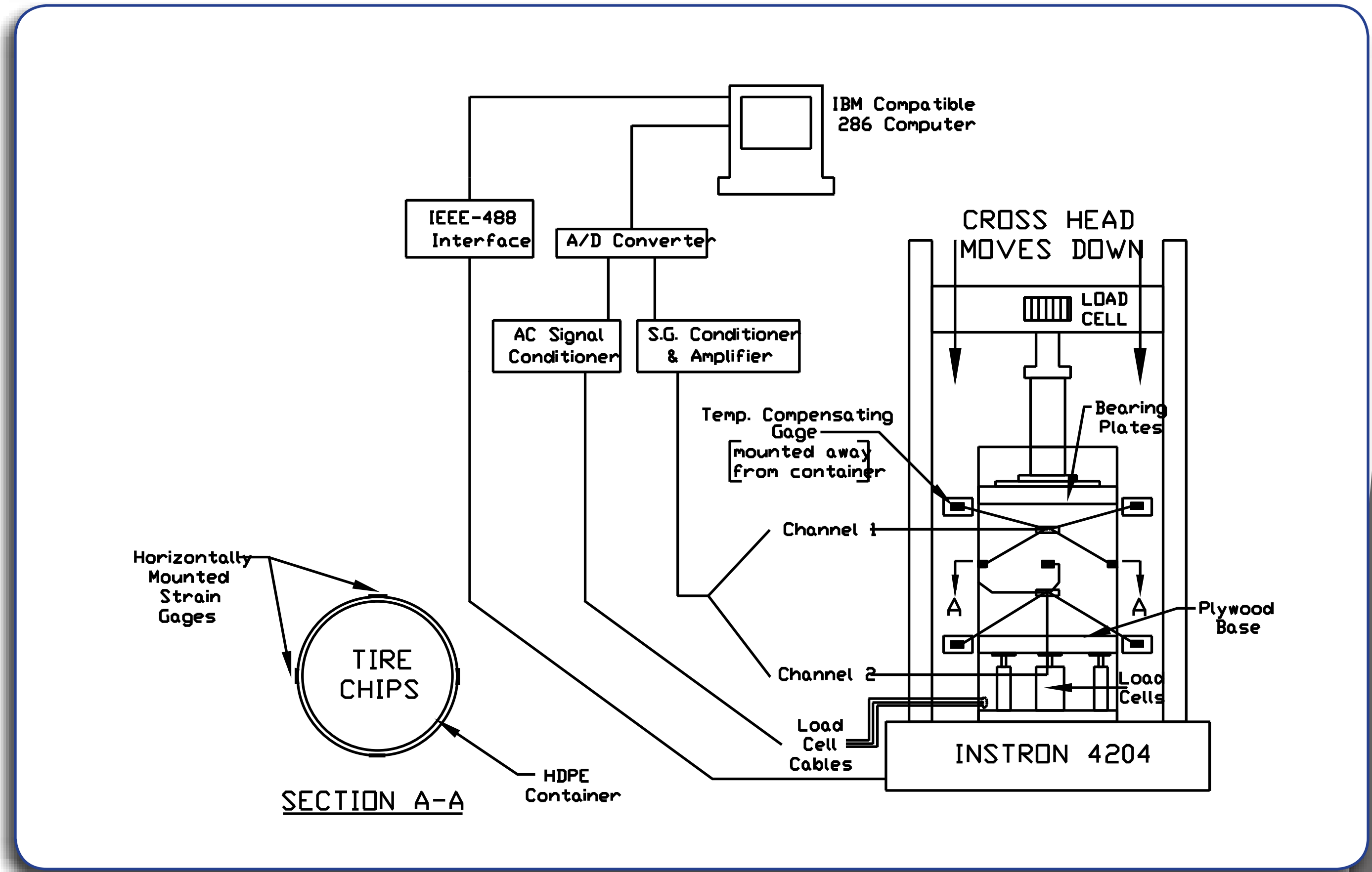


Exhibit C-2. Compressibility apparatus used by Nickels (Ref. 12)

diameter compaction molds and impact compaction. Compacted dry unit weights ranged from 0.61 to 0.69 Mg/m3 (38 to 43 pcf) (Ref.1).

The effect of compaction energy and compaction water content was investigated. Increasing the compaction energy from 60 percent of standard Proctor to 100 percent of modified Proctor increased the compacted unit weight by only 0.02 Mg/m3 (1.2 pcf), showing that compaction energy has only a small effect on the resulting unit weight. Unit weights were about the same for air-dried samples and samples at saturated surface dry conditions (about 4 percent water content), indicating that water content has a negligible effect on unit weight (Refs. 7, 11). One significance of this finding is that there is no need to control moisture content of TDA during field placement.

Measuring the compacted unit weight of TDA with a 300-mm (12-inches) maximum size is impractical in the laboratory. However, results from a highway embankment constructed with large TDA suggest that the unit weight of 300-mm (12-inches) maximum size TDA is less than for 75-mm (3-inches) maximum size TDA (Ref. 10).

COMPRESSIBILITY

The compressibility of TDA with a 75 mm (3 inches) maximum size has been measured in the laboratory. An apparatus used by Nickels (Ref. 12) had a 356-mm (14-inches) inside diameter and could accommodate a sample up to 356-mm (14-inches) thick. One challenge to measuring the compressibility of TDA is friction between the TDA and the inside wall of the test container. The apparatus used by Nickels (Ref. 12) uses load cells to measure the load carried by the specimen both at the top and bottom of the sample, as shown in Exhibit C-2. Even though Nickels used grease to lubricate the inside of the container, up to 20 percent of the load applied to the top of the sample was transferred to the walls of the container by friction. Compressibility of TDA with a 75 mm (3 inches) maximum size is shown in Exhibit C-3. The initial unit weights ranged from 0.51 to 0.64 Mg/m3 (32.1 to 40.1 pcf). There is a general trend of decreasing compressibility with increasing initial unit weight. The results for tests MD1 and MD4 are most applicable to using TDA as lightweight fill since their initial unit weight is typical of field conditions. Compressibility for stresses up to 480 kiloPascals (kPa) (70 pounds per square inch [psi]) are given by Manion and Humphrey (Ref. 11) and Humphrey and Manion

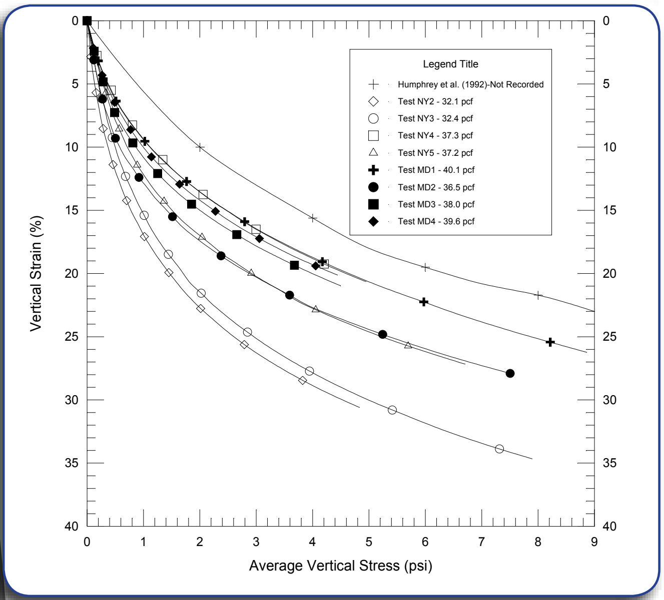


Exhibit C-3. Compressibility of TDA with a 3-inches (75-mm) maximum size (Ref. 12)

(Ref. 7). Laboratory data on the compressibility of TDA with a maximum size greater than 75 mm (3 inches) are not available; however, field measurements indicate that TDA with a 300-mm (12-inches) maximum size are less compressible than smaller TDA.

TIME-DEPENDENT SETTLEMENT

TDA exhibits a small amount of time-dependent settlement. Time-dependent settlement of thick TDA fills was measured by Tweedie and others (1997). Three types of TDA were tested with maximum sizes ranging from 38 to 75 mm (1.5 to 3 inches). The fill was 4.3 m (14 feet) thick and was surcharged with 36 kPa (750 psf), which is equivalent to about 1.8 m (6 feet) of soil. Vertical strain versus elapsed time is shown in Exhibit C-4. It is seen that time-dependent settlement occurred for about 2 months after the surcharge was placed. During the first 2 months, about 2 percent vertical strain occurred, which is equivalent to more than 75 mm (3 inches) of settlement for this 4.3-m (14-feet)-thick fill. The measurements are in general agreement with time-dependent laboratory compressibility tests conducted by Humphrey and others (Ref. 7). When TDA is used as backfill behind a pile supported bridge abutment or other structures that will experience little settlement, it is important to allow sufficient time for most of the time-dependent settlement of the TDA to occur before final grading and paving. Time-dependent settlement is of less concern when the ends of the TDA fill can be tapered from the full thickness to zero over a reasonable distance.

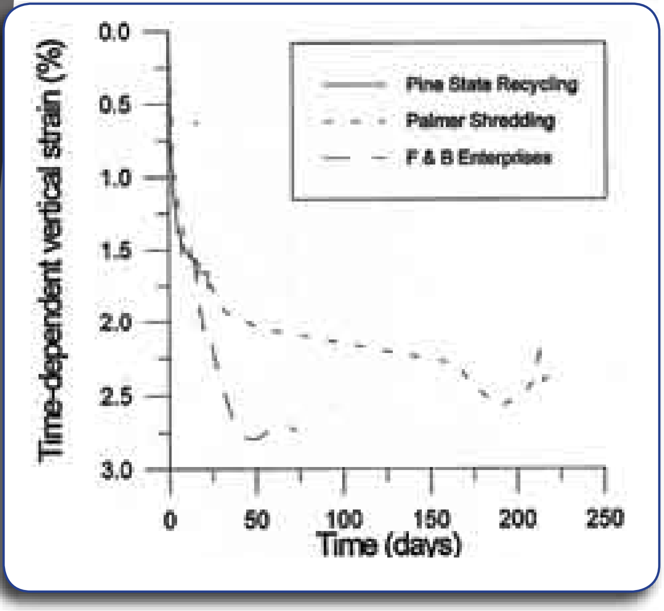


Exhibit C-4. Time-dependent settlement of TDA subjected to a surcharge of 750 psf (36 kPa) (Ref. 13)

SHEAR STRENGTH

The shear strength of TDA has been measured using direct shear and triaxial shear apparatus. The large TDA typically used for civil engineering applications requires that specimen sizes be several times larger than are used for common soils. This method has generally been used for TDA 25 mm (1inch) in size and smaller because of the limited availability of large triaxial shear apparatus. Moreover, the triaxial shear apparatus is generally not suitable if steel belts protrude from the cut edge of the TDA since the wires puncture the membrane used to surround the specimen.

The shear strength of TDA has been measured using triaxial shear (Refs. 2, 3, 4, 8); and using direct shear (Refs.5, 6, 7, 8, 9). Failure envelopes determined from direct shear and triaxial tests for TDA with a maximum size ranging from 9.5 to 900 mm (0.37 to 35 inches) are shown in Exhibit C-5. Data from Gebhard and others (Ref. 6) on larger size TDA fall in the same range. Available data suggest that shear strength is not affected by TDA size. Moreover, results from triaxial and direct shear tests are similar. Overall, the failure envelopes appear to be concave down. Thus, best fit linear failure envelopes are applicable only over a limited range of stresses. Friction angles and cohesion intercepts for linear failure envelopes for the data shown in Exhibit C-5 are given in Table C-1. TDA requires sufficient deformation to mobilize its strength (Ref. 8). Thus, a conservative approach should be taken when choosing strength parameters for TDA embankments founded on sensitive clay foundations.

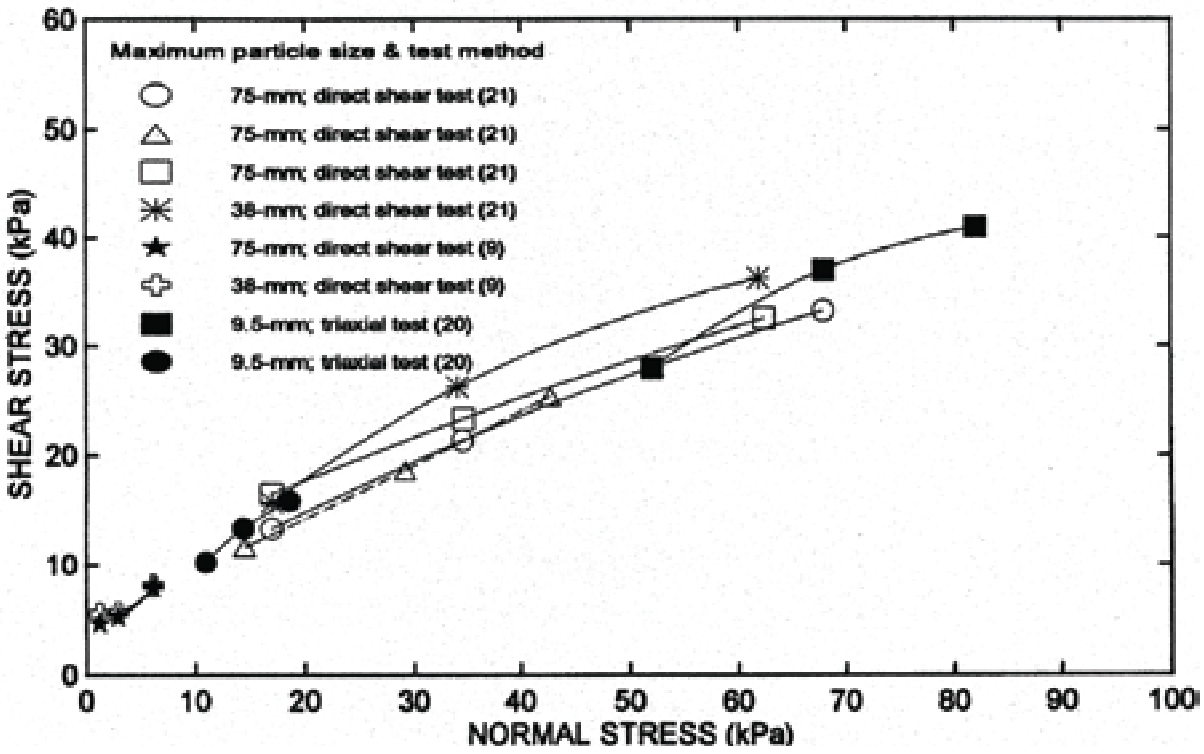


Exhibit C-5. Failure envelopes for TDA with maximum sizes ranging from 0.37 to 3 inches (9.5 to 75 mm)

Table C-1. Strength parameters for TDA.

Supplier	Maximum shred size		Test method	Applicable range of normal stress		Φ	Cohesion intercept	
	inches	mm		psf	kPa	deg.	psf	kPa
F&B	0.5	38	D.S.	360 to 1300	17 to 62	25	180	8.6
Palmer	3	75	D.S.	360 to 1300	17 to 62	19	240	11.5
Pine State	3	75	D.S.	360 to 1400	17 to 68	21	160	7.7
Pine State	3	75	D.S.	310 to 900	15 to 43	26	90	4.3
Dodger	35	900	D.S.	120 to 580	5.6 to 28	37	0	0
Unknown	0.37	9.5	Triaxial	1100 to 1700	52 to 82	24	120	6.0
Unknown	0.37	9.5	Triaxial	230 to 400	11 to 19	36	50	2.4

Note: D.S. = Direct Shear

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APPENDIX D

Calculation of Final In-Place Unit Weight and Overbuild

Final In-Place Unit Weight

The final in-place unit weight of the tire-derived aggregate (TDA) must be estimated during design. This unit weight is a necessary input for slope stability analysis and analysis of the stability of retaining walls. Estimation of the in-place unit weight must consider the immediate compression of the TDA under its self-weight and the weight of overlying soil and pavement. The calculation procedure is straightforward and is outlined below:

Step 1. From laboratory compaction tests or typical values, determine the initial uncompressed, compacted dry unit weight of TDA (γ_{di}) (for Type A TDA with a 75-mm [3-inches] maximum size, use 0.64 mg/m3 [40 pcf]).

Step 2. Estimate the in-place water content of TDA (w) and use the water content to determine the initial uncompressed, compacted total (moist) unit weight of TDA: $\gamma_{ti} = \gamma di\ (1+w)$. Unless better information is available, use w = 3 or 4 percent.

Step 3. Determine the vertical stress in center of TDA layer ($\sigma_{v\text{-}center}$). To calculate the vertical stress, hypothesize the compressed unit weight of TDA (γ_{tc}) (0.80 Mg/m^3 (50 pcf) is suggested for the first test).

$\sigma_{v\text{-}center} = t_{soil}(\gamma_{t\text{-}soil}) + (t_{TDA}/2)(\gamma_{tc})$

where: tsoil = thickness of overlying soil layer

$\gamma_{t\text{-}soil}$ = total (moist) unit weight of overlying soil

t_{TDA} = compressed thickness of TDA layer
(Note: In the equation, the thickness of the TDA layer is divided by 2 since the stress in the center of the layer is being computed.)

Step 4. Determine the percent compression (ε_v) using $\sigma_{v\text{-}center}$ and the measured laboratory compressibility of the TDA; for TDA with a 75-mm (3-inches) maximum size, use the results for test MD1 or MD4 in Exhibit D-1.

Step 5. Determine the compressed moist unit weight of the TDA: $\gamma_{tc} = \gamma_{ti}/(1\text{-}\varepsilon_v)$. If necessary, return to step 3 with a better estimate of the compressed moist unit weight.

This procedure was used to predict the compressed unit weight of a 4.3-m (14-feet) thick TDA fill covered by 1.8 m (6 feet) of soil built in Topsham, Maine. TDA with a 75-mm (3-inches) maximum size was used in the upper third of the fill, while TDA with a 150-mm (6-inches) maximum size was used in the lower part of the fill. The predicted compressed moist unit weight was 0.91 Mg/m3 (57 pcf). The actual in-place unit weight calculated from the final volume of the TDA zone and the weight of TDA delivered to the project was also 0.91 Mg/m3 (57 pcf). This validates the reliability of the laboratory compressibility tests and the procedure to estimate the compressed moist unit weight for TDA with maximum sizes between 75 and 150 mm (3 and 6 inches). However, when the procedure was applied to TDA with a 300-mm (12-inches) maximum size, the predicted unit weight was greater than determined in the field. For a highway embankment built in Portland, Maine, with TDA with a 300-mm (12-inches) maximum size, the predicted compressed moist unit weight was 0.93 Mg/m3 (58 pcf) compared with an actual unit weight of 0.79 Mg/m3 (49 pcf). The reasons for the difference appear to be a lower initial uncompressed unit weight and the lower compressibility for the larger TDA. It is recommended that the unit weight calculated using the procedure outlined above should be reduced by 15 percent for 300-mm (12-inches) maximum size TDA.

Calculation of Overbuild

TDA experiences immediate compression under an applied load, such as the weight of an overlying soil cover. The top elevation of the TDA layers should be overbuilt to compensate for this compression. The overbuild is determined using the procedure given below with the aid of a design chart (Exhibit D-2). The design chart was developed using a combination of laboratory compressibility tests and compression data measured from field projects. Exhibit D-2 is applicable to Type-B TDA (300-mm [12-inches] maximum size) that has been placed and compacted in 300-mm (12-inches)-thick layers. To use this procedure with smaller Type A TDA (3-inches maximum size), increase the calculated overbuild by 30 percent.

The overbuild for a single TDA layer is derived directly from Exhibit D-2. First, calculate the vertical stress that will be applied to the top of the TDA layer as the sum of the unit weights multiplied by the thicknesses of the overlying layers. Second, enter Exhibit D-2 with the calculated vertical stress and the final compressed thickness of the TDA layer to find the overbuild. Consider the following example:

0.229 m pavement at 2.56 Mg/m^3

0.610 m aggregate base at 2.00 Mg/m^3

0.610 m low permeability soil cover at 1.92 Mg/m^3

3.05-m (10 feet) thick TDA layer

The vertical stress applied to the top of the TDA layer would be:

(0.229 m x 2.56 Mg/m3 x 9.81 m/s2) + (0.610 m x 2.00 Mg/m3 x 9.81 m/s2) + (0.610 m x 1.92 Mg/m3 x 9.81 m/s2) = 29.1 kPa x 20.884 psf/kPa = 610 psf

Enter Exhibit D-2 with 610 psf (29.1 kPa) and using the line for a TDA layer thickness of 10 feet (3.05 m) results in an overbuild of 0.68 feet (0.21 m). Round to the nearest 0.1 m. Thus, an overbuild of 0.2 m is necessary.

The overbuild for the bottom TDA layer of a two-layer cross-section is also determined directly from Exhibit D-2. The procedure is the same as described above for a single TDA layer. Consider the following example:

0.229 m pavement at 2.56 Mg/m^3

0.610 m aggregate base at 2.00 Mg/m^3

0.610 m low permeability soil cover at 1.92 Mg/m^3

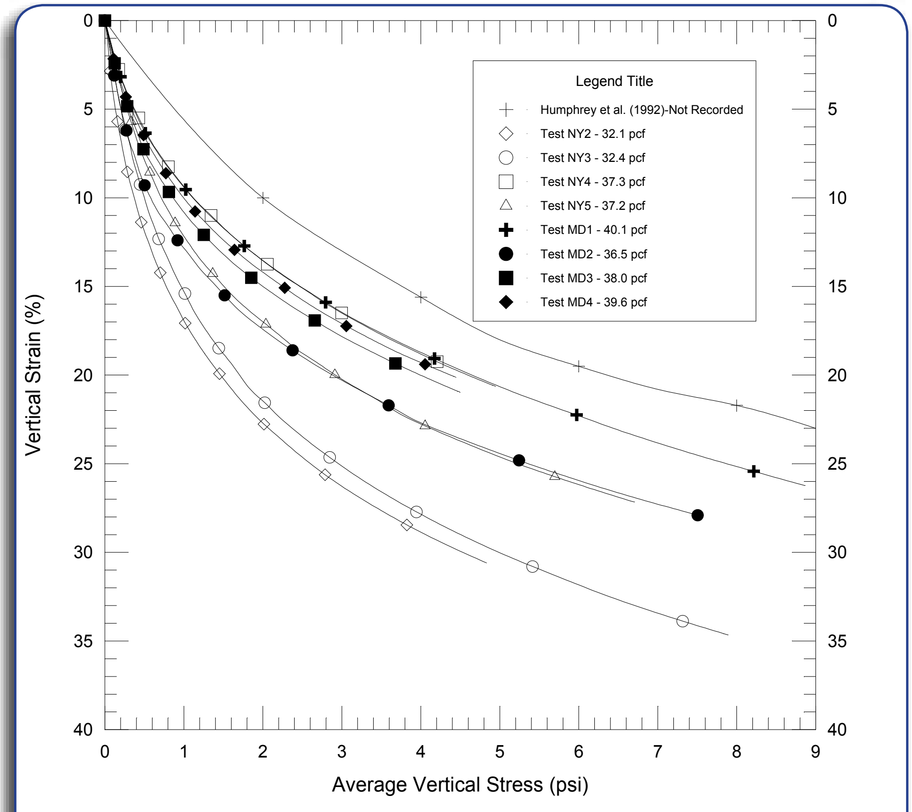
3.05-m (10 feet) thick TDA layer at 0.80 Mg/m^3

0.915 m soil separation layer at 1.92 Mg/m^3

3.05-m (10 feet) thick lower TDA layer

The vertical stress applied to the top of the TDA layer would be:

(0.229 m x 2.56 Mg/m^3 x 9.81 m/s2) + (0.610 m x 2.00 Mg/m^3 x 9.81 m/s^2) + (0.610 m x 1.92 Mg/m^3 x 9.81 m/s^2) + (3.05 m x 0.80 Mg/m3 x 9.81 m/s2) + (0.915 m x



(Note: 1 psi = 144 psf = 6.895 kPa)

Exhibit D-1. Compressibility of Type A TDA at low stresses (Ref. 1)

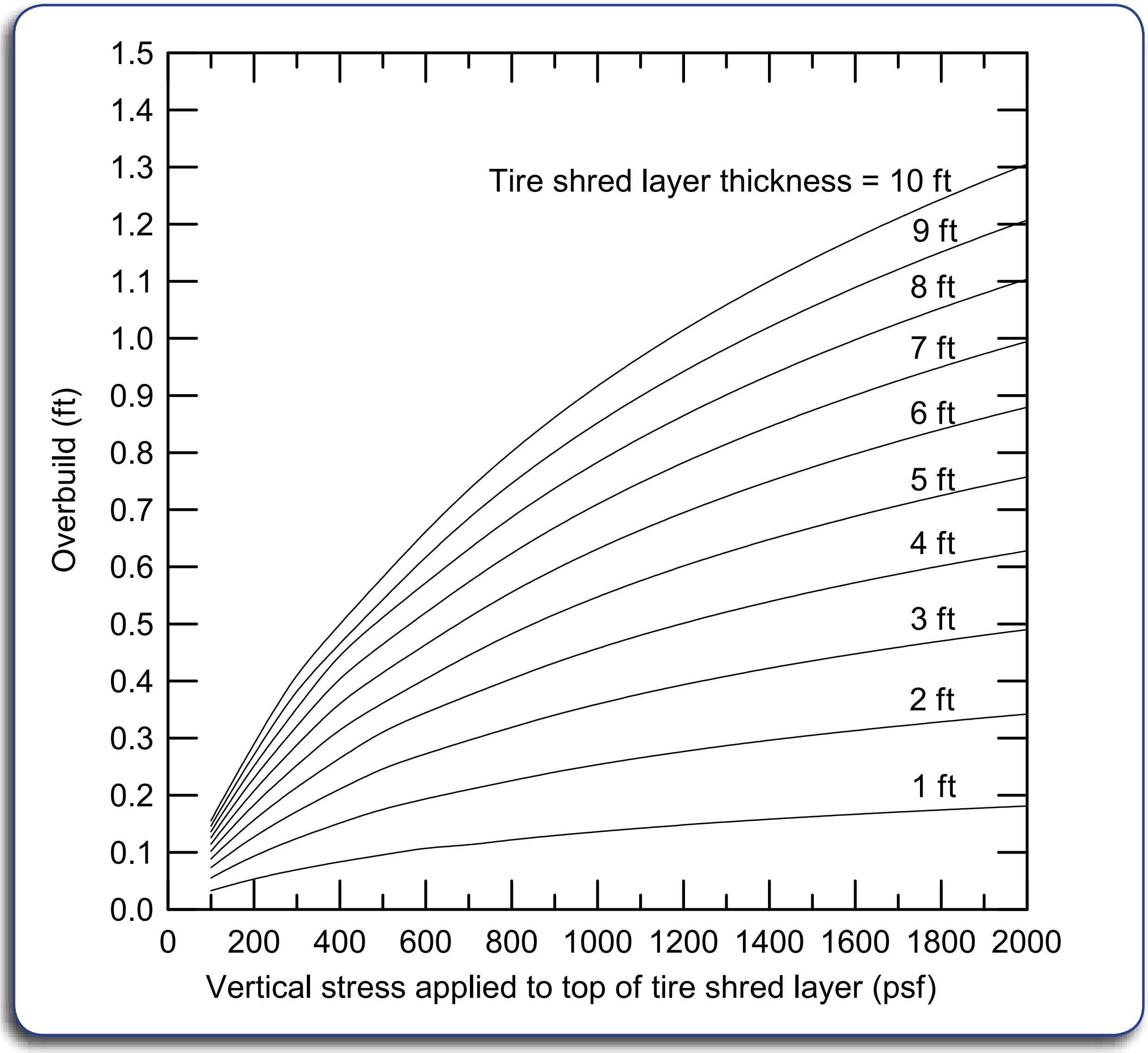


Exhibit D-2. Overbuild design chart for Type B TDA

1.92 Mg/m^3 x 9.81 m/s^2)= 70.4 kPa x 20.884 psf/kPa = 1,470 psf

Enter Exhibit D-2 with 1470 psf (70.4 kPa) and using the line for a TDA layer thickness of 10 feet (3.05 m) results in an overbuild of 1.13 feet (0.34 m). Round to the nearest 0.1 m. Thus, the use of a 0.3-m overbuild for the lower TDA layer is needed.

The overbuild of the top elevation for the upper TDA layer of a two-layer cross-section must include both the compression of the upper TDA layer when the pavement, base, and soil cover is placed, and the compression of the lower TDA layer that will still occur under the weight of these layers. In other words, the lower TDA layer has not yet compressed to its final thickness. This final compression will only occur once the embankment reaches final grade. Therefore, the question is, "How much compression of the lower TDA layer will occur due to placing the pavement, base and soil cover?" Consider the same two-layer example used above.

0.229 m pavement at 2.56 Mg/m^3

0.610 m aggregate base at 2.00 Mg/m^3

0.610 m low permeability soil cover at 1.92 Mg/m^3

3.05-m (10 feet) thick TDA layer at 0.80 Mg/m^3

0.915 m soil separation layer at 1.92 Mg/m^3

3.05-m (10 feet) thick lower TDA layer

Step 1. The final vertical stress applied to the top of the upper TDA layer would be: (0.229 m x 2.56 Mg/m3 x 9.81 m/s2) + (0.610 m x 2.00 Mg/m3 x 9.81 m/s2) + (0.610 m x 1.92 Mg/m3 x 9.81 m/s2) = 29.1 kPa x 20.884 psf/kPa = 610 psf. Enter Exhibit D-2 with 610 psf (29.1 kPa) and using the line for a TDA layer thickness of 10 feet (3.05 m) results in a compression of 0.68 feet (0.21 m).

Step 2. Once the upper TDA layer (but not the top soil cover) is in place, the vertical stress applied to the top of the lower TDA layer would be: (3.05 m x 0.80 Mg/m^3 x 9.81 m/s2) + (0.915 m x 1.92 Mg/m^3 x 9.81 m/s^2) = 41.1 kPa x 20.884 psf/kPa = 860 psf. To determine the compression of the lower TDA layer that has occurred up to this point, enter Exhibit D-2 with 860 psf (41.1 kPa) and using the line for a TDA layer thickness of 10 feet (3.05 m) results in a compression of 0.84 feet (0.26 m).

Step 3. Once the embankment reaches its final grade, the vertical stress applied to the top of the lower TDA layer would be 70.4 kPa = 1470 psf, as calculated previously. Enter Exhibit D-2 with 1470 psf (70.4 kPa) and using the line for a TDA layer thickness of 10 feet (3.28 m) results in an overbuild of 1.13 feet (0.34 m). (Note: rounding to 0.3 m would give the overbuild of the lower TDA layer.)

Step 4. Subtract the result from Step 2 from the result of Step 3 to obtain the compression of the lower TDA layer which will occur when the pavement, base, and soil cover is placed: 0.34 m – 0.26 m = 0.08 m.

Step 5. Sum the results from Steps 1 and 4 to obtain the amount the top elevation of the upper TDA layer should be overbuilt. 0.21 m + 0.08 m = 0.29 m (0.95 feet). Round to the nearest 0.1 m. Thus, the elevation of the top of the upper TDA layer should be overbuilt by 0.3 m.

Final result: Overbuild the top elevation of the lower TDA layer by 0.3 m and the upper TDA layer by 0.3 m.

Reference

1. Nickels, W.L., Jr. 1995. “The Effect of Tire Chips as Subgrade Fill on Paved Roads.” M.S. Thesis, Department of Civil Engineering, University of Maine, Orono, Maine, 215 pp.

APPENDIX E

Case Histories – Use of TDA as Lightweight Embankment Fill

Case History – Portland Jetport Interchange

Tired derived aggregate (TDA) was used as lightweight fill for construction of two 9.8-m (32-feet)-high highway embankments in Portland, Maine (Ref. 5). These embankments were the approach fills to a new bridge over the Maine Turnpike. The bridge is part of a new interchange that provides better access to the Portland Jetport and Congress Street. This site was underlain by about 12.2 m (40 feet) of weak marine clay. Test results indicated that the clay is an overconsolidated, moderately sensitive, inorganic clay of low plasticity. Undrained shear strength varied from approximately 72 kiloPascals (kPa) (1,500 pounds per square foot [psf]) near the top to 19 kPa (400 psf) near the center of the layer.

The designers for the project (the Maine offices of HNTB, Inc., and Haley and Aldrich, Inc., and the University of Maine) found that embankments built of conventional soil were too heavy, resulting in an unacceptably low factor of safety against slope instability. They looked at several ways to strengthen the foundation soils, but these methods were too costly. Construction of the embankments using lightweight fill was chosen as the lowest cost alternative. They considered several types of lightweight fill, including TDA, expanded polystyrene insulation boards, and expanded shale. TDA was chosen because it was $300,000 cheaper than the other alternatives. Moreover, the project would put some 1.2 million tires to a beneficial end use. Wick drains were also used to accelerate consolidation of the foundation soils.

Project Layout and Construction

Several steps were taken to comply with the guidelines to limit heating of thick TDA fills (Refs. 1, 2). The guidelines required that a single TDA layer be no thicker than 3 m (10 feet). Therefore, the TDA layer was broken up into two layers, each up to 3 m (10 feet) thick, separated by 0.9 m (3 feet) of soil, as shown in Exhibit E-1. Low-permeability soil with a minimum of 30 percent passing the No. 200 sieve was placed on the outside and top of the fill to limit inflow of air and water. The final precaution to limit heating was to use large Type B TDA with a minimum of fines. The TDA had less than 50 percent by weight passing the 75-mm (3-inches) sieve, 25 percent passing the 38-mm (1½-inches) sieve, and less than 1 percent passing the No. 4 sieve. The TDA had a maximum size measured in any direction of 300 mm (12 inches) to ensure that it could be easily placed with conventional construction equipment. The embankment was topped with 0.61 m (2 feet) of

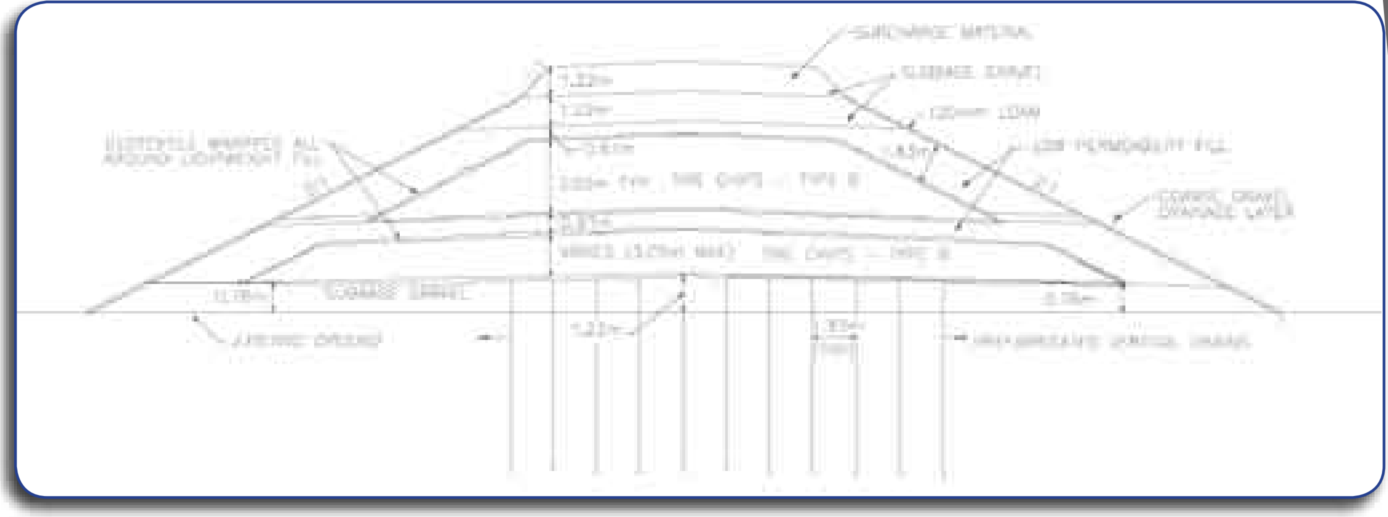


Exhibit E-1. Cross section through embankment constructed on soft marine clay for the Portland Jetport Interchange (Ref. 5)

Exhibit E-2. Caterpillar D-4 spreading TDA for lightweight embankment fill at Portland Jetport Interchange

low-permeability soil, 1.22 m (4 feet) of granular soil, plus 1.22 m (4 feet) of temporary surcharge. The purpose of the surcharge was to increase the rate of consolidation of the soft clay foundation soils and was unrelated to the TDA fill.

The TDA was placed with conventional construction techniques. First, geotextile was placed on the prepared base to act as a separator between the TDA and surrounding soil. Then, the TDA was spread in 300-mm (12-inch)-thick lifts using a Caterpillar D-4 dozer, as shown in Exhibit E-2. Each lift was compacted with six passes of a vibratory roller with a minimum 9.8-metric ton (10-ton) operating weight. After the TDA was in place, the contractor placed a geotextile separator on the sides and top of the TDA zone. The surrounding soil cover was placed as the TDA was placed.

Construction Settlement and In-place Unit Weight

Settlement plates were installed at the top and bottom of each TDA layer to monitor settlement. Compression of each TDA layer at the end of fill placement is summarized in Table E-1. The compression predicted based on laboratory compression tests on 75-mm (3-inches) maximum size TDA is also shown. It is seen that the predicted compression is significantly greater than the measured value. Thus, the compressibility of TDA with a 300-mm (12-inches) maximum size appears to be less than for 75-mm (3-inches) maximum size TDA. This compression was one factor that led to overpredicting the final in-place unit weight. The final in-place unit weight was predicted to be 0.93 Mg/m3 (58 pcf) compared with an actual value of 0.79 Mg/m3 (49 pcf), a difference of 18 percent. This difference cannot be entirely accounted for by the difference in compressibility. Thus, it is likely that the initial (uncompressed) unit weight of the larger TDA is less than for 75-mm (3-inches) maximum size TDA.

Temperature Measurements

Monitoring the temperatures of the TDA fill was of great interest because of past problems with heating of thick TDA fills (Ref. 4). The warmest temperatures were measured at the time of placement when the black TDA was heated by exposure to direct sunlight. Initial temperatures ranged from 24 to 38°C (75 to 100°F). After it was covered with the first few lifts of fill, the temperatures began dropping with time. Temperatures were still dropping when monitoring was discontinued in April 1998. Typical temperature measurements are shown on Exhibit E-3. From these results, it can be seen that there was no evidence of self-heating.

Case History – North Abutment Approach Fill

The key element of the Topsham Brunswick Bypass Project was the 300-m (984-feet) long Merrymeeting Bridge over the Androscoggin River. The subsurface profile at the location of the north abutment consisted of 3 to 6 m (10 to 20 feet) of marine silty sand overlying 14 to 15 m (45 to 50 feet) of marine silty clay. The clay is underlain by glacial till and then bedrock. The existing riverbank had a factor of safety against a deep-seated slope failure that was near 1. Moreover, the design called for an approach fill leading up to the bridge abutment that would

Table E-1.Measured compressibility of TDA layer for Portland Jetport Interchange project.

Settlement Plate No.	Location	Lower TDA layer		Upper TDA layer	
		Measured	Predicted	Measured	Predicted
SW1	25+00,C/L	12.6%	22%	8.3%	14%
SW4	26+00, C/L	13.4%	21%	11.2%	14%
SE1	30+00, C/L	19.1%	22%	10.9%	14%
SE4	31+00, C/L	17.3%	23%	9.3%	14%
Avg. C/L Plates		15.6%	22%	9.9%	14%

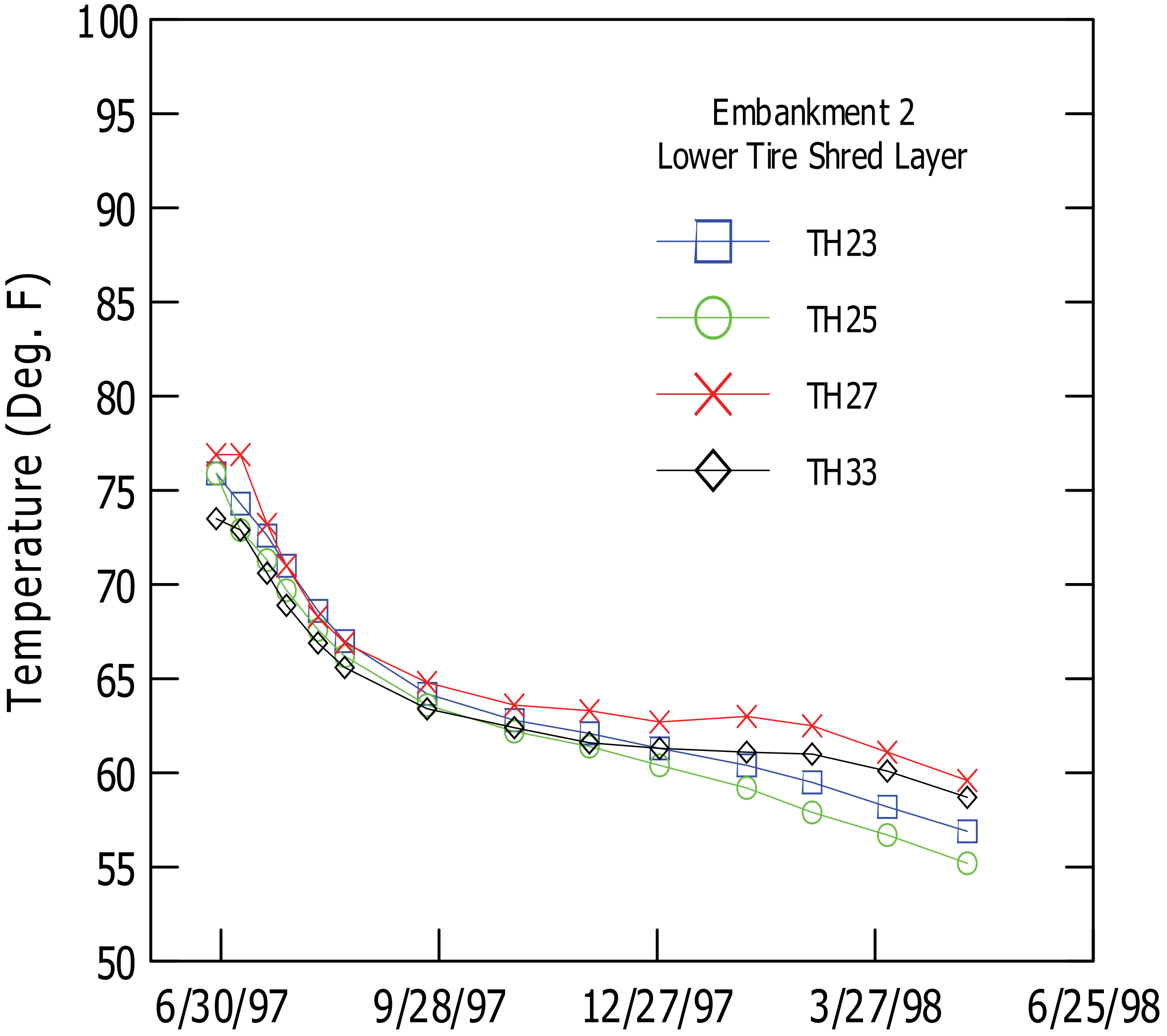


Exhibit E-3. Temperatures in lower tire shed layer of lightweight embankment fill at Portland Jetport Interchange

have further lowered the factor of safety. Thus, it was necessary to both improve the existing factor of safety and allow construction of the approach fill. The best solution was to excavate some of the existing riverbank and replace it with a 4.3-m (14-foot)-thick layer of TDA. TDA had the added advantage of reducing lateral pressures against the abutment wall. Other types of lightweight fill were considered, including geofoam and expanded shale aggregate. However, TDA proved to be the lowest-cost solution. The project used some 400,000 scrap tires (Ref. 9).

Project Layout and Construction

The surficial marine sand was excavated to elevation 5.2 m (17 feet) and then the abutment wall supported by an H-pile was constructed. A 4.3-m (14 foot)-thick zone of TDA was placed from station 53+50.6 m (175+50 feet) to the face of the abutment wall at station 53+72.0 m (176+20 feet). The fill tapers from a thickness of 4.3 m (14 feet) at station 53+50.6 m (175+50 feet) to zero thickness at station 53+35.4 m (175+00 feet) to provide a gradual transition between the TDA layer and the conventional fill. It was estimated that the TDA layer would compress 460 mm (18 inches) from the weight of the overlying soil layers. As a result, the layer was built up an additional 460 mm (18 inches) so that the final compressed thickness would be 4.3 m (14 feet). The TDA layer was enclosed in a woven geotextile (Niolon Mirafi 500X) to prevent infiltration of surrounding soil. The TDA was spread with front-end loaders and bulldozers and then compacted by six passes of a smooth drum vibratory roller (Bomag BW201AD) with a static weight of 9,432 kg (10.4 tons). The thickness of a compacted lift was limited to 305 mm (12 inches). It was determined that approximately 15 inches (381 mm) of loose TDA needed to be initially placed to obtain a compacted thickness of 305 mm (12 inches). TDA placement began on September 25, 1996, and was completed on October 3, 1996. A longitudinal section of the

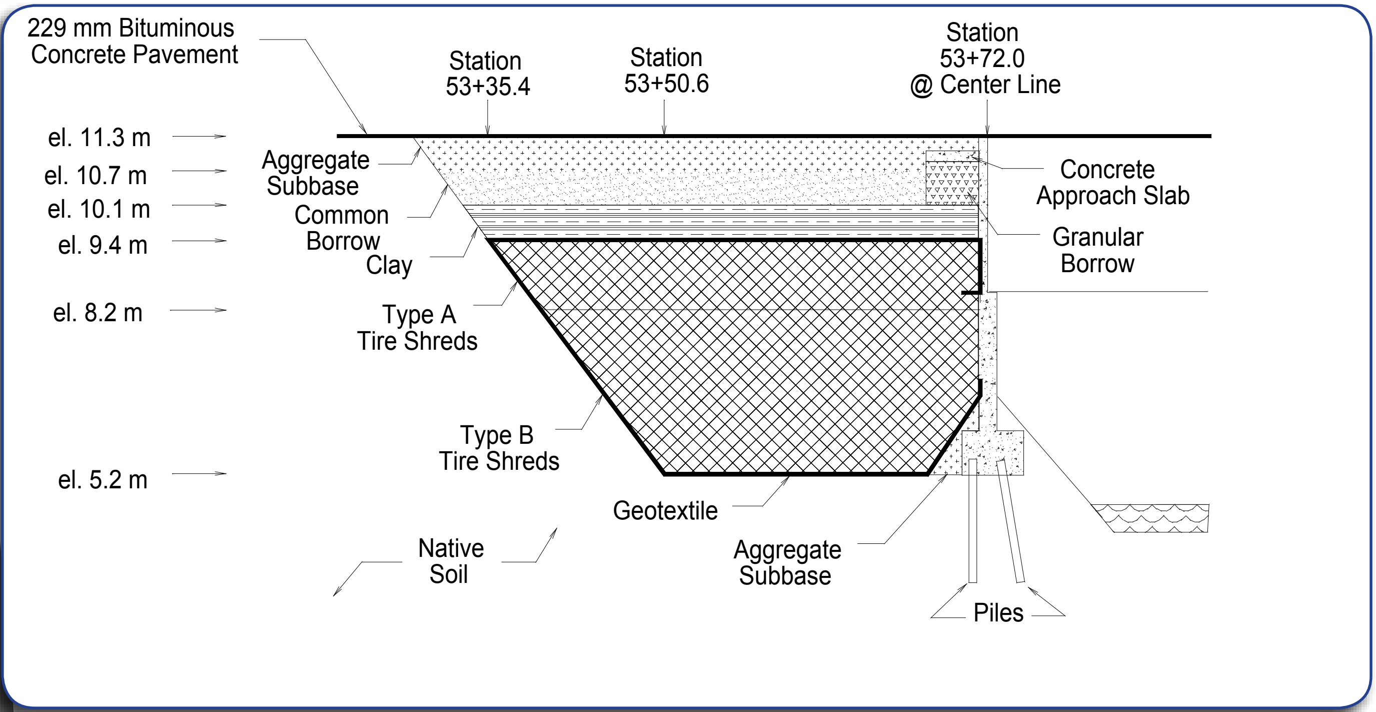


Exhibit E-4. Longitudinal section through North Abutment TDA fill

completed abutment and embankment is shown in Exhibit E-4.

This project was designed and built before the guidelines were developed to limit self-heating of TDA fills. However, the project included design features to limit self-heating. The first was to use larger Type B TDA in the lower portion of the fill from elevation 5.2 m (17 feet) to elevation 8.2 m (27 feet). The Type B TDA was specified to have a maximum dimension measured in any direction of 305 mm (12 inches); a minimum of 75 percent (by weight) passing the 203-mm (8-inches) square mesh sieve, a maximum of 25 percent (by weight) passing the 38-mm (1½-inches) square mesh sieve, and a maximum of 5 percent (by weight) passing the No. 4 (4.75-mm) sieve. No requirement for the percent passing the 3-inches (75-mm) sieve was included for this project. Gradation tests showed that the TDA generally had a maximum dimension smaller than 150 mm (6 inches). Type A TDA, with a maximum size of 75 mm (3 inches), were placed from elevation 8.2 m (27 feet) to the top of the TDA fill. It would have been preferable to use the larger Type B TDA for the entire thickness. However, a significant quantity of Type A TDA had already been stockpiled near the project prior to the decision to use larger TDA. It was judged that it would be acceptable to use the smaller Type A TDA in the upper portion of the fill. Moreover, it would have been preferable to limit the total thickness of the TDA layer to 3 m (10 feet), as recommended by the guidelines to limit self-heating.

As an additional step to reduce the possibility of self-heating, the TDA are overlain by a layer of compacted clayey soil with a minimum of 30 percent passing the No. 200 (0.075 mm) sieve. The purpose of the clay layer is to minimize the flow of water and air though the TDA. The clay layer is approximately 0.61 m (2 feet) thick and is built up in the center to promote drainage toward the side slopes. A 0.61-m (2-foot)-thick layer of common borrow was placed over the clay layer. Overlying the common borrow is 0.76 m (2.5 feet) of aggregate subbase.

TDA undergoes a small amount of time-dependent settlement. For this project, a thick TDA fill adjoined a pile-supported bridge abutment, leading to concerns that there could be differential settlement at the junction with the abutment. However, Tweedie and others (Ref. 6) showed that most of the time-dependent settlement occurs within the first 60 days. To accommodate the time-dependent settlement before paving, the contractor was required to place an additional 0.3 m (1 foot) of subbase aggregate as a surcharge to be left in place for a minimum of 60 days. In fact, the overall construction schedule allowed the contractor to leave the surcharge in place from October 1996 through October 1997. The surcharge was removed in October 1997 and the roadway was topped with 229 mm (9 inches) of bituminous pavement. The highway was opened to traffic on November 11, 1997. Additional construction information is given in Cosgrove and Humphrey (Ref. 3).

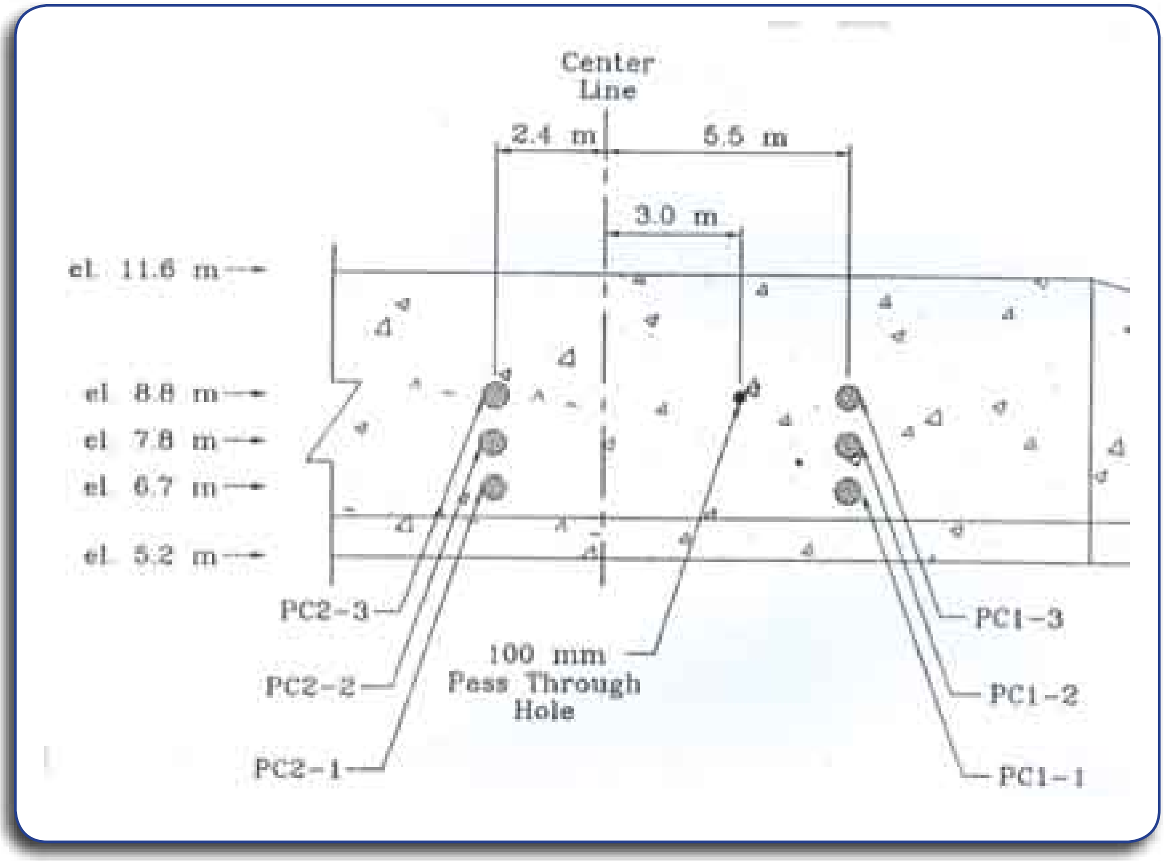


Exhibit E-5. Location of pressure cells in North Abutment (Ref. 3)

Instrumentation

Four types of instruments were installed: pressure cells cast into the back face of the abutment wall; and vibrating wire settlement gauges, settlement plates, and temperature sensors placed in the TDA fill. Vibrating wire pressure cells were installed to monitor lateral earth pressure against the abutment wall. Three Roctest model TPC pressure cells (PC1-1, PC1-2, and PC1-3) were installed on the face of the abutment wall 4 m (13 feet) right of centerline, and three Roctest model EPC pressure cells (PC2-1, PC2-2, and PC2-3) were installed 4 m (13 feet) left of centerline, as shown in Exhibit E-5. TDA was placed against all the cells.

Measured Horizontal Pressure and Settlement

The lateral pressure at the completion of TDA placement (October 3, 1996), completion of soil cover, and placement of surcharge (October 9, 1996) is summarized in Table E-2. Lateral pressures on October 31, 1996, are also shown. It is seen that the pressures increased with depth at completion of TDA placement. However, at completion of soil cover and surcharge placement, the pressures recorded by cells PC1-1, PC1-2, and PC1-3 were nearly constant with depth and ranged between 17.05 and 19.61 kPa (356 and 410 psf). These findings are consistent with at-rest conditions measured on an earlier project (Tweedie and others 1997; 1998a). Cells PC2-1, PC2-2, and PC2-3 showed different behavior. At completion of TDA placement 9, 1996, cell PC2-2 showed a pressure of 30.22 kPa (631psf), while cell PC2-1, located only 1.07 m (3.5 feet) lower, was 20.04 kPa (418 psf) and cell PC2-3, located 1.07 m (3.5 feet) above PC2-2, was 12.31 kPa (257 psf). These cells were the less stiff EPC cells. Large scatter has been observed with EPC cells on an earlier TDA project (Refs. 6, 7, 8). This scatter is thought to be caused, at least in part, when the large TDA creates a non-uniform stress distribution on the face of the pressure cell. The average pressure recorded by the three PC2 cells was 20.85 kPa (435 psf), which is slightly higher than the PC1 cells. Between October 9, 1996 and October 31, 1996, the lateral pressure increased by 1 to 2 kPa (20 to 40 psf). The pressures have been approximately constant since that time.

The TDA fill compressed about 370 mm (14.6 inches) during placement of the overlying soil cover. In the next 60 days, the fill settled an additional 135 mm (5.3 inches). Between December 15, 1996, and December 31, 1997, the fill underwent an additional 15 mm (0.6 inches) of time-dependent settlement. The rate of settlement had decreased to a negligible level by late 1997. The total compression of the TDA fill was 520 mm (20.4 inches) which was 13 percent greater than

Table E-2. Summary of Lateral Pressures on Abutment Wall.

Date	PC1-1	PC2-1	PC1-2	PC2-2	PC1-3	PC2-3
	Cell elev. = 6.70 m		Cell elev. = 7.77m		Cell elev. = 8.84 m	
10/3/96[2]	7.84[1]	7.41	6.04	7.27	2.62	1.41
10/9/96[3]	17.04	20.04	19.61	30.22	17.05	10.91
10/31/96	18.27	21.05	20.98	32.84	20.24	12.31

[1] Horizontal pressure in kPa.
[2] Date TDA placement completed.
[3] Date soil cover and surcharge placement completed.

the 460 mm (18 inches) that was anticipated based on laboratory compression tests. The difference is the result, at least in part, of time-dependent settlement that is not accommodated in the short-term laboratory tests. The final compressed density of the TDA was about 0.9 Mg/m3 (57 pcf), higher than for the Portland Jetport Project, most likely because of the smaller size of the TDA used for this project.

Temperature of TDA Layer

A small amount of self-heating of the TDA occurred. Five out of the 12 thermistors in the Type A TDA experienced a peak temperature of between 30 and 40°C (86 and 104°F). In contrast, only two of the 18 thermistors in the larger Type B TDA experienced a peak in this range, and these two sensors may have been influenced by warmer overlying Type A TDA. This difference suggests that larger TDA is less susceptible to heating. In any case, the peak temperatures were too low to be of concern. Since early 1997, the overall trend has been one of decreasing temperature. However, the temperature of the TDA appears to be slightly influenced by seasonal temperature changes.

References

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8. Tweedie, J.J., Humphrey, D.N., and Sandford, T.C. 1998b. “Tire TDA as Retaining Wall Backfill, Active Conditions.” Journal of Geotechnical and Geoenvironmental Engineering. ASCE, Vol. 124, No. 11. pp. 1061-1070.

9. Whetten, N., Weaver, J. Humphrey, D., and Sandford, T. 1997. “Rubber Meets the Road in Maine.” Civil Engineering, Vol. 67, No. 9. September. pp. 60-63.

APPENDIX F

Comparative Transportation Cost Example

	Vehicle Type			
	Pickup Truck		**Pickup with Trailer**	
	Basis	**Cost/mile**	**Basis**	**Cost/mile**
Labor ($/hr)	$10/hour, 30 miles/hour	$0.33	$10/hour, 30 miles/hour	$0.33
Fuel ($/mile)	$4.00/gallon, 15 miles/gallon	$0.27	$4.00/gallon, 12 miles/gallon	$0.33
Maintenance($/mile)	$1000/yr, 30,000 miles/yr	$0.03	$2000/yr, 30,000 miles/yr	$0.07
Subtotal-Variable Cost		$0.63		$0.73
Insurance	$1000/yr, 30,000 miles/yr	$0.03	$1000/yr, 30,000 miles/yr	$0.03
Depreciation	$2500/yr, 30,000 miles/yr	$0.08	$2500/yr, 30,000 miles/yr	$0.08
ROI	$15,000x20%= $3,000/yr	$0.10	$18000x20%= $3600/yr	$0.12
Subtotal-Fixed Cost		$0.22		$0.24
Total costs		$0.85		$0.97
Tires/load		50		250
Cost/mile/tire	for 1 mile	$0.02	for 1 mile	$0.004
	for 25 miles	$0.43	for 25 miles	$0.10
	for 100 miles	$1.70	for 100 miles	$0.39
	for 200 miles	$3.40	for 200 miles	$0.78
	for 500 miles	$8.50	for 500 miles	$1.94
	Box Truck		**Tractor with 48 foot trailer**	
	Basis	**Cost/mile**	**Basis**	**Cost/mile**
Labor ($/hr)	$12/hour, 30 miles/hour	$0.40	$15/hour, 30 miles/hour	$0.50
Fuel ($/mile)	$4.00/gallon, 8 miles/gallon	$0.50	$4.00/gallon, 6 miles/gallon	$0.67
Maintenance($/mile)	$2500/yr, 30,000 miles/yr	$0.08	$3500/yr, 30,000 miles/yr	$0.12
Subtotal-Variable Cost		$0.98		$1.28
Insurance	$2000/yr, 30,000 miles/yr	$0.07	$3000/yr, 30,000 miles/yr	$0.07
Depreciation	$3500/yr, 30,000 miles/yr	$0.12	$10000/yr, 30,000 miles/yr	$0.33
ROI	$25000x20%= $5000/yr	$0.17	$80000x20%= $16000/yr	$0.53
Subtotal-Fixed Cost		$0.35		$0.93
Total costs		$1.33		$2.22
Tires/load		400		1,400
Cost/mile/tire	for 1 mile	$0.003	for 1 mile	$0.002
	for 25 miles	$0.08	for 25 miles	$0.04
	for 100 miles	$0.33	for 100 miles	$0.16
	for 200 miles	$0.67	for 200 miles	$0.32
	for 500 miles	$1.67	for 500 miles	$0.79

APPENDIX G

Scrap Tire Processing Facility Economic Parameters

BASIS

The projected operating mode is a single facility capable of receiving and processing 250,000 to 1,000,000 passenger tire equivalents (PTEs)/year into specific shredded product sizes ranging from Class B tire-derived aggregate (TDA) to 1-inch nominal chips

SITE PARAMETERS

Property Size:

Approximately 5 acres of flat, dry land in a central location with highway access and stable soil, plus additional property for product storage if more than 1 month's inventory is required.

Property Use:

3 acres for site operations, equipment movement and limited tire storage

2 acres for office and maintenance trailers and limited product storage, as well as water storage if applicable

Common Property Improvements:

Fenced and gated perimeter provides access control to decrease theft, vandalism, and arson

Operating area lighting, and possibly storage area lighting (depending on surroundings), enhances operating flexibility, safety, and security

Soil stabilization of storage and working areas: (1) decreases tire contamination and associated equipment maintenance, and (2) decreases product contamination for greater marketability and value

Concrete over about 1 acre of the centralized operating area prevents water displaced from tires during handling and processing; creating wet and undesirable conditions. A berm (3 to 4 feet high) around the perimeter of the storage area controls dispersion of pyrolytic oil or water if there is a fire.

Water accessibility or a water storage pond (lined if necessary) for emergency fire fighting

Electrical power for processing equipment, including a transformer if the available power is not stepped down

Office and associated equipment required to conduct business

Shop area and tools required to maintain equipment

Basic operation can be conducted outside, but efficiency may be impaired by weather. A portable cover may be desirable for shredder maintenance.

Additional Product Storage Requirements:

Depending on the products and markets, seasonal markets may require inventory up to 80 percent of annual production in an environmentally safe manner that minimizes the probability of a fire and maximizes the ability to control a fire if one occurs. Such an inventory would require an additional:

5 acres for 10 piles 50 x 150 x 10 feet (with 50 feet clear around each one) for storage of 800,000 PTEs of TDA

About 760 meters (2,500 linear feet) of fencing to enclose this area

EQUIPMENT FOR TYPE B TDA

Processing - If the sole product is Type B TDA, one of the least expensive single machines to purchase and maintain is the Barclay 4.9-inch horizontal primary shredder mounted at a 45-degree angle with a classification and recycle system. Alternatives include tire shredders with 4-inch knife spacing, but these generally have higher capital and operating costs. The major components and approximate current costs in $US are as follows:

Shredder with extended infeed conveyor	$230,000
Classifier	$45,000
Recycle conveyors (local supply)	$36,000
Discharge conveyor (local supply)	$50,000
Transportation (estimated from California)	$5,000
Equipment Subtotal	**$366,000**
Installation (approximate)	$75,000
Spare parts	$40,000
Miscellaneous and contingency	$100,000
Total processing equipment	**$581,000**

Additional Equipment – Required for movement of tires and shreds

Front end loader (used)	$60,000
Supplemental Bobcat	$20,000
Electrical supply/controls (estimate)	$25,000
Dump truck/trailer for on-site shred movement	$20,000
Total additional equipment	**$125,000**

FOR NOMINAL 2 INCH SHREDS (3-4 INCH MAX SIZE)

Processing - Normal use is a single high-capacity tire shredder with a classification and recycle system for volumes up to 1 million tires/year. The major components and approximate current costs in $US are as follows:

Shredder	$350,000 - $500,000
Infeed conveyor/mechanical system	$ 25,000 - $150,000
Classifier	$ 45,000 - $230,000
Recycle conveyors (local supply)	$ 36,000
Discharge conveyor (local supply)	$ 50,000
Transportation (estimated)	$ 12,000 - $ 20,000
Equipment Subtotal	**$518,000 - $986,000**
Installation (approximate)	$100,000
Spare parts	$ 60,000
Miscellaneous and contingency	$125,000
Total processing equipment	**$803,000 -$1,271,000**

Additional Equipment – Required for movement of tires and shreds

Front end loader (used)	$60,000
Supplemental Bobcat	$20,000
Electrical supply/controls (estimate)	$ 25,000
Dump truck/trailer for on-site shred movement	$ 20,000
Total additional equipment	**$125,000**

FOR NOMINAL 1 INCH SHREDS

Processing – Processing capital costs will be the same as for 2-inch shreds, but magnets may be required to remove chips that contain bead wire for some applications. If there is no market or reasonable disposal alternative for this material (30 to 40 percent), then additional equipment can be installed to liberate the wire for sale (as previously discussed) and salvage the rubber in a variety of sizes down to crumb rubber. The major components and approximate current costs in $US are as follows:

Total 2-inch equipment	$803,000 - $1,271,000
Additional magnets/conveyors	$ 60,000 -$ 110,000
Total processing equipment	**$863,000 -$1,381,000**
Additional cost for wire liberation/recovery/ Classification equipment to produce saleable wire and some crumb rubber products	$500,000 -$1,200,000

OPERATING COST COMPONENTS

Typical Staffing level for one shift/5 day operation (some jobs can be combined in low-volume operations)

- 1 Manager
- 1 Office/accounting
- 1 Shipment receiving/monitoring
- 1 Supervisor/maintenance manager
- 1 Loader operator
- 1-2 Laborer/maintenance

Professional Services (such as accounting, marketing, and legal)

Processing/Maintenance

For Class B TDA

Processing equipment maintenance	$ 6.00/ton
Loader/Bobcat maintenance	$ 2.00/ton
Power for Equipment	

For 1.0 million tires/year
(150 hp x 70% load x .746 kilowatt [kW] conversion = 78 kW/hour x 2,080 hours/yr = 162,240 kW/year)

For 0.5 million tires/year, est 50 % load factor or 115,000 kW/year

For 0.25 million tires/year, est 40 % load or 92,000 kW/yr

For 2-inch nominal shreds

Processing equipment maintenance	$15.00/ton
Loader/Bobcat maintenance	$ 2.00/ton
Power for Equipment	

For 1.0 million tires/year

(250 hp x 70% load x .746 kW conversion = 131 kW/hour x 2,080 hours/yr = 272,480 kW/year)

For 0.5 million tires/year, est 50% load factor or 195,000 kW/year

For 0.25 million tires/year, est 40% load or 156,000 kW/yr

For 1-inch nominal shreds

Processing equipment maintenance	$25.00/ton
Loader/Bobcat maintenance	$ 2.00/ton
Power for Equipment	

For 1.0 million tires/year

(250 hp x 85%load x .746 kW conversion = 159 kW/hour x 2,080 hours/yr = 330,000 kW/year)

For 0.5 million tires/year, est 70% load factor or 272,000 kW/year

For 0.25 million tires/year, est 55% load or 213,000 kW/yr

OTHER FIXED COST COMPONENTS

Insurance

Financing

Government Taxes

APPENDIX H

Comparative Volume Sensitivity of Tire Processing Facilities

TIRE-DERIVED AGGREGATE (TDA) PRODUCT

VARIABLE COSTS

COST COMPONENT	**PROCESSING RATE (Tires/year)**								
	250,000			**500,000**			**1,000,000**		
	Number	**Cost/year**	**Cost/tire**	**Number**	**Cost/year**	**Cost/tire**	**Number**	**Cost/year**	**Cost/tire**
Labor									
Supervisor	1	$40,000	$0.16	1	$40,000	$0.08	1	$40,000	$0.04
Manual	2	$48,000	$0.19	2	$48,000	$0.10	3	$72,000	$0.07
Subtotal	3	$88,000	$0.35	3	$88,000	$0.18	4	$112,000	$0.11
Power (mw/yr) @ $100/mw	92	$9,200	$0.04	115	$11,500	$0.02	162	$16,200	$0.02
Maintenance									
Shredder ($/ton)	6	$15,000	$0.06	6	$30,000	$0.06	6	$60,000	$0.06
Other ($/ton)	2	$5,000	$0.02	2	$10,000	$0.02	2	$20,000	$0.02
Subtotal	8	$20,000	$0.08	8	$40,000	$0.08	8	$80,000	$0.08
Wire Disposal (tons)	0	-	-	0	-	-	0	-	-
TOTAL VARIABLE COST		$117,200	$0.47		$139,500	$0.28		$208,200	$0.21

Depreciation (real with tire processing equipment – typically 5 – 8 years)

FIXED COSTS

COST COMPONENT	PROCESSING RATE (Tires/year)								
	250,000			500,000			1,000,000		
	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire
Administration									
Manager	1	$50,000	$0.20	1	$50,000	$0.10	1	$50,000	$0.05
Sales/service	By Mgr	-	-	By Mgr	-	-	1	$40,000	$0.04
Clerical	1	$20,000	$0.08	1	$20,000	$0.04	1	$20,000	$0.02
Office expense		$18,000	$0.07		$18,000	$0.04		$18,000	$0.02
Prof. Services		$5,000	$0.02		$10,000	$0.02		$10,000	$0.01
Subtotal		$93,000	$0.37		$98,000.00	$0.20		$138,000.00	$0.14
Capital charges									
Amortization (12.5%/year)		$97,813	$0.39		$97,813	$0.20		$97,813	$0.10
General Expense									
Insurance (1% of $1M)		$10,000	$0.04		$10,000	$0.02		$10,000	$0.01
Prop Tax (1% of $1M)		$10,000	$0.04		$10,000	$0.02		$10,000	$0.01
Subtotal		$20,000	$0.08		$20,000	$0.04		$20,000	$0.02
TOTAL FIXED COSTS		$210,813	$0.84		$215,813	$0.43		$255,813	$0.26
TOTAL COST		$328,013	$1.31		$355,313	$0.71		$464,013	$0.46
PROFIT (25% ROC on $1M)		$250,000	$1.00		$250,000	$0.50		$250,000	$0.25
TOTAL PRICE		$578,013	$2.31		$605,313	$1.21		$714,013	$0.71

COMPARATIVE VOLUME SENSITIVITY OF TIRE PROCESSING FACILITIES

NOMINAL 2-INCH SHREDS

VARIABLE COSTS

COST COMPONENT	PROCESSING RATE (Tires/year)								
	250,000			500,000			1,000,000		
	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire
Labor									
Supervisor	1	$40,000	$0.16	1	$40,000	$0.08	1	$40,000	$0.04
Manual	2	$48,000	$0.19	2	$48,000	$0.10	3	$72,000	$0.07
Subtotal	3	$88,000	$0.35	3	$88,000	$0.18	4	$112,000	$0.11
Power (mw/yr) @ $100/mw	156	$15,600	$0.06	195	$19,500	$0.04	272	$27,200	$0.03
Maintenance									
Shredder($/ton)	15	$37,500	$0.15	15	$75,000	$0.15	15	$150,000	$0.15
Other($/ton)	2	$5,000	$0.02	2	$10,000	$0.02	2	$20,000	$0.02
Subtotal	17	$42,500	$0.17	17	$85,000	$0.17	17	$170,000	$0.17
Wire Disposal(tons)	0	-	-	0	-	-	0	-	-
TOTAL VARIABLE COST		$146,100	$0.58		$192,500	$0.39		$309,200	$0.31

FIXED COSTS

COST COMPONENT	PROCESSING RATE (Tires/year)								
	250,000			500,000			1,000,000		
	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire
Administration									
Manager	1	$50,000	$0.20	1	$50,000	$0.10	1	$50,000	$0.05
Sales/service	By Mgr	-	-	By Mgr	-	-	1	$40,000	$0.04
Clerical	1	$20,000	$0.08	1	$20,000	$0.04	1	$20,000	$0.02
Office expense		$18,000	$0.07		$18,000	$0.04		$18,000	$0.02
Prof. Services		$5,000	$0.02		$10,000	$0.02		$10,000	$0.01
Subtotal		$93,000	$0.37		$98,000	$0.20		$138,000	$0.14
Capital charges									
Amortization (12.5%/year)		$150,000	$0.60		$150,000	$0.30		$150,000	$0.15
General Expense									
Insurance (1% of $1.5M)		$15,000	$0.06		$15,000	$0.03		$15,000	$0.02
Prop Tax (1% of $1.5M)		$15,000	$0.06		$ 15,000	$0.03		$15,000	$0.02
Subtotal		$30,000	$0.12		$30,000	$0.06		$30,000	$0.03
TOTAL FIXED COSTS		$273,000	$1.09		$278,000	$0.56		$318,000	$0.32
TOTAL COST		$288,000	$1.15		$293,000	$0.59		$333,000	$0.33
PROFIT (25% ROC on $1.5M)		$375,000	$1.50		$375,000	$0.75		$375,000	$0.38
TOTAL PRICE REQUIRED		$663,000	$2.65		$668,000	$1.34		$708,000	$0.71

COMPARATIVE VOLUME SENSITIVITY OF TIRE PROCESSING FACILITIES

NOMINAL 1-INCH SHREDS

VARIABLE COSTS

COST COMPONENT	PROCESSING RATE (Tires/year)								
	250,000			500,000			1,000,000		
	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire
Labor									
Supervisor	1	$40,000	$0.16	1	$40,000	$0.08	1	$40,000	$0.04
Manual	2	$48,000	$0.19	2	$48,000	$0.10	3	$72,000	$0.07
Subtotal	3	$88,000	$0.35	3	$88,000	$0.18	4	$112,000	$0.11
Power (mw/yr) @ $100/mw	213	$21,300	$0.09	272	$27,200	$0.05	330	$33,000	$0.03
Maintenance									
Shredder($/ton)	25	$62,500	$ 0.25	25	$125,000	$0.25	25	$250,000	$0.25
Other($/ton)	2	$5,000	$0.02	2	$10,000	$0.02	2	$20,000	$0.02
Subtotal	27	$67,500	$0.27	27	$135,000	$0.27	27	$270,000	$0.27
Wire Disposal(tons)	50	$1,500	$0.01	100	$3,000	$0.01	200	$6,000	$0.01
TOTAL VARIABLE COST		$178,300	$0.71		$253,200	$0.51		$421,000	$0.42

FIXED COSTS

COST COMPONENT	PROCESSING RATE (Tires/year)								
	250,000			500,000			1,000,000		
	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire	Number	Cost/year	Cost/tire
Administration									
Manager	1	$50,000	$0.20	1	$50,000	$0.10	1	$50,000	$0.05
Sales/service	By Mgr	-	-	By Mgr		-	1	$40,000	$0.04
Clerical	1	$20,000	$0.08	1	$20,000	$0.04	1	$20,000	$0.02
Office expense		$18,000	$0.07		$18,000	$0.04		$18,000	$0.02
Prof. Services		$5,000	$0.02		$10,000	$0.02		$10,000	$0.01
Subtotal		$93,000	$0.37		$98,000	$0.20		$138,000	$0.14
Capital charges									
Amortization (12.5%/year)		$162,500	$0.65		$162,500	$0.33		$162,500	$0.16
General Expense									
Insurance (1% of $1.6M)		$16,000	$0.06		$16,000	$0.03		$16,000	$0.02
Prop Tax (1% of $1.6M)		$16,000	$0.06		$16,000	$0.03		$16,000	$0.02
Subtotal		$ 32,000	$0.13		$32,000	$0.06		$32,000	$0.03
TOTAL FIXED COSTS		$287,500	$1.15		$292,500	$0.59		$332,500	$0.33
TOTAL COST		$303,500	$1.21		$308,500	$0.62		$348,500	$0.35
PROFIT (25% ROC on $1.6M)		$400,000	$1.60		$400,000	$0.80		$400,000	$0.40
TOTAL PRICE		$703,500	$2.81		$708,500	$1.42		$748,500	$0.75