TRANSFORMING END OF LIFE TIRES INTO A RESOURCE: THE ROLE OF

TIRE DERIVED AGGREGATES

IN CIVIL ENGINEERING

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Acknowledgments

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Executive Summary

Tire-derived aggregate (TDA) offers a sustainable solution for addressing the environmental challenges posed by the approximately 330 million tires discarded annually in the U.S. and Canada. TDA, produced by repurposing end-of-life tires, serves as a viable alternative to traditional aggregates in civil and environmental engineering. However, its usage remains limited in construction projects over the past decade, signalling a significant opportunity for expansion.

TDA presents unique engineering properties, such as lightweight composition, high porosity, vibration mitigation, and thermal insulation, making it suitable for diverse applications like drainage systems, noise barriers, and road construction. Additionally, TDA's high shear strength and permeability, coupled with freeze-thaw mitigation, reduce lateral loads and enhance drainage performance. Research confirms TDA's cost-effectiveness and sustainability, offering consistent material quality and reducing the environmental impact associated with natural aggregate extraction and greenhouse gas emissions.

Environmental studies on TDA demonstrate its safety in engineering applications, showing that while metals and synthetic organic compounds may leach from TDA, their concentrations remain below regulatory thresholds. Furthermore, these leached substances are quickly immobilized by the soil matrix, reducing risks to aquatic life and ecosystems. TDA also acts as a contaminant cleaner, interacting with metals like iron and zinc to precipitate or adsorb pollutants, further mitigating environmental concerns.

In conclusion, TDA not only supports sustainable construction by lowering costs and promoting recycling but also aligns with circular economy principles by minimizing waste and emissions. Expanding TDA use in infrastructure projects will enhance environmental performance, reduce reliance on natural aggregates, and unlock further engineering benefits through innovative applications.

Disclaimer

This State of Knowledge Report on Tire-Derived Aggregates (TDA) is intended to complement, not replace, existing design practices. It provides insights into successful applications of TDA and outlines specific recommendations for its use in civil and environmental engineering projects. While the report highlights best practices and identifies potentially unfavourable scenarios, it is essential to follow the suggested preventive measures when applying TDA in these situations. The guidance offered is advisory in nature, and users are encouraged to exercise professional judgment and adhere to current industry standards throughout the design and construction phases. Misuse of TDA, or failure to follow the recommended guidelines, could result in project challenges. With careful planning and proper implementation, TDA projects can achieve their intended outcomes and ensure long-term performance.

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Introduction

1. INTRODUCTION

1.1. Purpose, Motivation, and Intended Audience

The purpose of this state-of-knowledge report on the use of tire-derived aggregates (TDA) in civil engineering applications is to compile and synthesize existing research and practical experiences to provide a comprehensive overview of this innovative material. This report aims to inform stakeholders about the benefits, limitations, and best practices associated with TDA usage. It seeks to highlight the environmental and economic advantages of recycling scrap tires into usable aggregate material, as well as to identify the technical properties and performance characteristics that make TDA suitable for various engineering applications. By consolidating current knowledge, the report serves as a valuable resource for decision-makers looking to adopt sustainable and cost-effective materials in their projects.

The motivation behind this report stems from the growing need for sustainable construction practices and the desire to reduce environmental impacts associated with traditional construction materials. With increasing awareness of the environmental issues posed by scrap tire disposal and the continuous search for innovative engineering solutions, TDA presents a promising alternative. The intended audience for this report includes civil engineers, construction managers, urban planners, environmental scientists, policymakers, and academic researchers. By providing detailed insights and practical guidelines, the report aims to support these professionals in making informed decisions about integrating TDA into their projects, ultimately promoting sustainable development and resource conservation in the civil engineering and construction industry.

1.2.Background - What Is TDA?

The global volume of scrap tires is projected to escalate from 1.5 billion to a staggering 5 billion annually by 2030 (Moasas et al., 2022). This rapid increase in scrap tire generation presents a multitude of potential public health and environmental hazards. Discarded tires not only contribute to pollution and habitat destruction but also serve as breeding grounds for disease-carrying mosquitoes, thereby heightening the risk of vector-borne diseases (Cecich et al., 1996). Hence, efficient recycling and repurposing of these tires is not just a solution to these risks but also a significant step towards sustainable development, as it aids in waste reduction and conserves natural resources.

Tire Derived Aggregate (TDA) refers to shredded or chipped scrap tires repurposed as a construction material. Characterized by their lightweight, durability, excellent drainage properties, and superior damping capacity, TDA is utilized in a wide variety of civil engineering projects. It offers an eco-friendly alternative to traditional materials for various applications, including lightweight fill for embankments and retaining walls, drainage media in septic system drain fields, backfill above and around pipes, and as shock absorption layers in vibration control applications. By using TDA, we not only mitigate the environmental impact of accumulated tires and promote recycling but also achieve cost-effective performance-enhancing solutions.

1.3.ASTM Definition of TDA

The American Society for Testing and Materials (ASTM) has established the Standard Practice for the Use of Scrap Tires in Civil Engineering Applications (Practice for Use of Scrap Tires in Civil

Figure 1.1. a) Tire fire in Minto, NB (Source: New Brunswick, 2019); b) Old tires are breeding grounds for disease-carrying mosquitoes.

ASTM D6270-20). This standard provides comprehensive guidelines for assessing the physical properties, design considerations, construction techniques, and potential leachate production associated with processed scrap tires. It promotes the use of scrap tires as a viable alternative to traditional civil engineering materials such as stone, gravel, soil, sand, and other lightweight aggregates and fill materials.

In ASTM D6270, TDA is generally described as "pieces of scrap tires that have a basic geometrical shape and are generally between 3 and 12 inches (76 to 300 mm) in size. These pieces are intended for use in various civil engineering applications, including road construction, landfill projects, and building foundations".

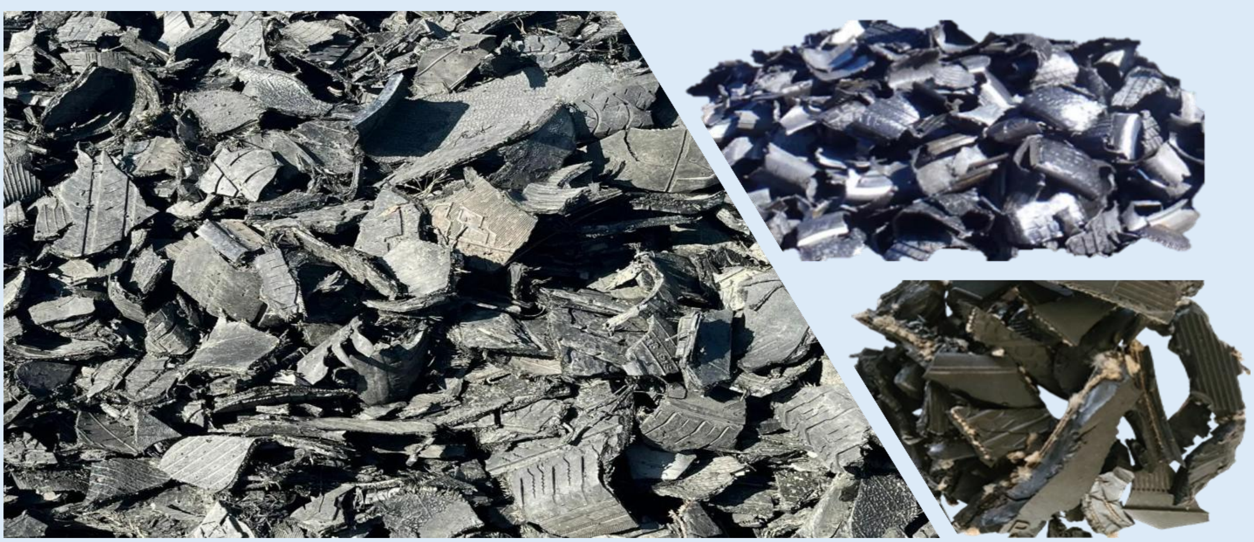


Figure 1.2. Tire Derived Aggregates

ASTM D6270 classifies tire-derived aggregate into two types. Type A TDA, with a maximum aggregate size of 250 mm and 100 % passing the 100-mm square mesh sieve, is primarily used for applications such as insulation, drainage, backfilling above and around pipes, and vibration dampening. On the other hand, the larger Type B TDA, which has a maximum aggregate size of 450 mm, is best suited for use as a lightweight backfill material in embankments and behind retaining walls.

1.4.Chemical Composition of Tires

The chemical composition of tires is complex and varies depending on the type and intended use. Typically, tires are composed of natural and synthetic rubber, along with a variety of reinforcing materials and chemicals. Natural rubber, derived from the latex of rubber trees, and synthetic rubber, produced from petroleum-based materials, form the primary elastomers in tires. On average, a typical tire comprises approximately 19% natural rubber and 24% synthetic rubber

(Rouse, 2005). Additionally, carbon black is a significant component used to reinforce the rubber and improve durability. Carbon black constitutes about 28% of the tire's composition. Various chemicals are added to enhance performance, including sulphur (1%) for vulcanization, which cross-links the rubber molecules to increase elasticity and strength. Other additives include zinc oxide (1%), stearic acid (1%), and antioxidants (1%) to protect against ozone and UV degradation. Silica, which can make up about 10% of the tire, is also used to improve wet traction and reduce rolling resistance. Other components, such as fabric and steel reinforcements, make up the remaining 15%, providing structural integrity and strength. Collectively, these components contribute to the tire's overall performance, durability, and safety.

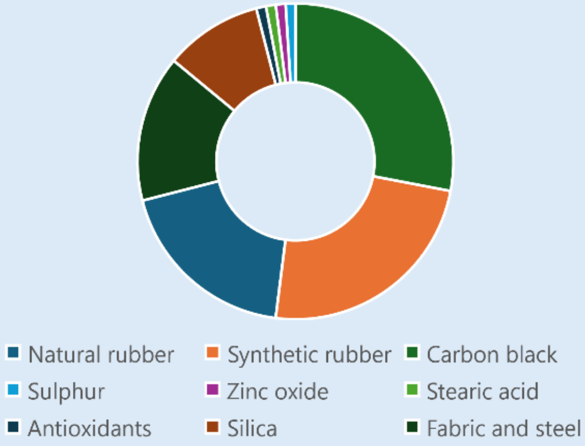


Figure 1.3. Typical chemical composition of tires. (after Rouse, 2005)

1.5 TDA Production

The production of Tire-Derived Aggregates involves a comprehensive recycling process that starts with the collection of end-of-life tires. These discarded tires are collected from various sources, such as tire retailers, automotive service centers, and municipal waste facilities. The collected tires are then transported to recycling facilities equipped with specialized shredding machines. The process starts by feeding the tires into a primary shredder. Once the material is fed into the machine, it is immediately engaged and shredded by two cutting blade shafts. These blades work continuously, cutting and reducing the material into irregular-sized pieces. These machines use slow-speed, high-tolerance cutters to produce clean cuts and minimize the amount of exposed wire, resulting in what is known as rough shreds. Following the cutting stage, the shreds undergo screening to capture oversized pieces and return them to the shredding process for further reduction in size. Also, screening to remove fines is sometimes needed, this is more common for tires sourced from an outside stockpile where they may have picked up soil. The next stage involves removing excess wire by either a head pulley magnet or a cross-belt magnet, which is sometimes needed to meet the requirements for free steel and excess wire exposed at the cut edges. TDA serves as a foundational feedstock material in the tire recycling industry. It is often the first product generated by end-of-life tire processors, who shred whole tires into a TDA-like material as the initial step in transforming ELTs into various downstream products. From this starting point, TDA can be further processed into crumb rubber for use in rubberized asphalt or molded products, or it may serve as Tire-Derived Fuel (TDF) in energy recovery applications. Even in cases where tires are destined for landfill disposal, they are often first shredded into a TDA form to reduce volume and alter their physical characteristics for regulatory compliance. Thus, TDA occupies a critical position in the tire life cycle, acting as the gateway material for multiple value-added applications or final disposal pathways.

Depending on the desired size and application, the material can undergo further shredding to meet specific standards, such as ASTM D6270 for Type A and Type B TDA.

Figure 1.4. Tire shredder (courtesy of Liberty Tire Recycling)

The final TDA product is then subjected to quality control tests to verify its engineering properties, such as permeability, compressibility, and thermal conductivity, ensuring compliance with ASTM standards and making it a reliable and sustainable material for construction projects.

1.6 Benefits of Using TDA

The use of tire-derived aggregate offers a sustainable, cost-effective, and high-performing alternative to traditional construction materials, contributing to both environmental conservation and improved engineering outcomes. Here are some key advantages:

1.6.1 Environmental Benefits

Tire-derived aggregate offers significant environmental benefits through recycling, repurposing waste tires, and displacing virgin materials. By converting discarded tires into TDA, the volume of waste directed to landfills is substantially reduced, alleviating the environmental burden and conserving landfill space. Additionally, TDA serves as a sustainable alternative to conventional construction materials like gravel and crushed stone, reducing the need for natural resource extraction and lowering the overall carbon footprint of construction projects.

TDA has a considerably lower density compared to conventional fill materials, allowing haul trucks to carry larger volumes within legal weight limits, minimizing the number of trips and mitigating several environmental and logistical challenges associated with heavy construction traffic. Fewer truck trips to complete a typical fill project is particularly advantageous in reducing the carbon footprint.

Moreover, TDA exhibits excellent drainage properties, making it highly effective in civil engineering applications such as road construction, retaining wall backfill, and drainage layers in landfills. These properties help in mitigating waterlogging and soil erosion, contributing to improved water management and soil conservation. The lightweight nature of TDA also reduces the energy consumption and emissions associated with transportation and handling compared to traditional materials. Overall, the use of TDA not only promotes tire recycling but also supports sustainable construction practices, enhancing environmental health and resource efficiency.

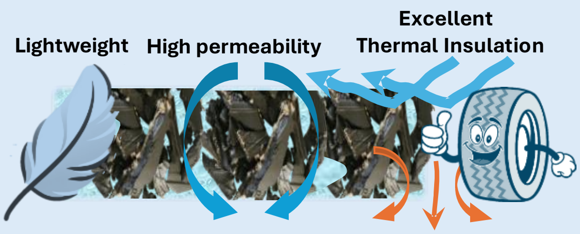
1.6.2 Social Benefits

Tire-derived aggregate offers several compelling social benefits that are increasingly capturing the attention of policymakers. By diverting millions of end-of-life tires from landfills and illegal dumping sites, TDA supports environmental stewardship while reducing public health risks associated with tire stockpiles, such as fires and mosquito breeding grounds. Its use in civil engineering projects can improve infrastructure resilience and lower maintenance costs, which translates to more efficient use of public funds. Additionally, TDA creates opportunities for local job creation in the recycling and manufacturing sectors, promoting circular economy principles. These multifaceted social advantages make TDA not only an environmentally sound choice but also a socially responsible one.

1.6.3 Engineering Benefits

Using TDA in engineering projects offers numerous benefits, primarily in enhancing material performance and sustainability.

TDA possesses unique physical properties such as high permeability, low density, and excellent thermal insulation. These characteristics make TDA particularly valuable in civil engineering applications like road construction, landfill drainage, and embankment fills. For instance, the high permeability of TDA helps improve drainage systems by preventing waterlogging and reducing hydrostatic pressure, thereby enhancing the longevity and stability of structures. Additionally, their lightweight nature reduces the load on underlying soils, mitigating settlement issues and making TDA ideal for use in soft ground conditions.



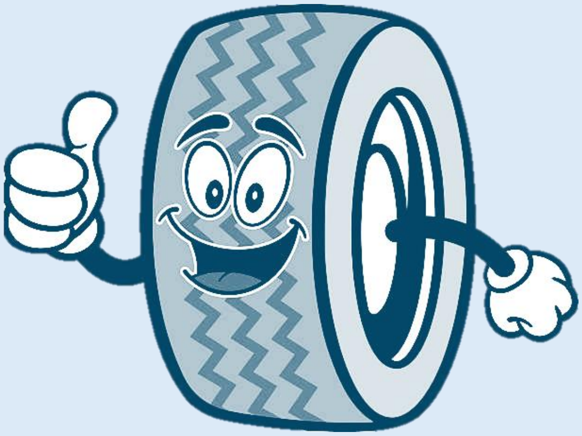
Some important features of TDA

1.6.4 Cost Benefits

TDA is generally less expensive than conventional materials due to the abundance of scrap tires and the relatively low processing costs. Additionally, using TDA can reduce the need for natural resource extraction, which further lowers project costs. This affordability makes TDA an attractive option for projects with tight budgets while still meeting engineering requirements.

Furthermore, incorporating TDA in certain applications can lead to significant long-term cost savings. For example, using TDA to prevent frost-heave damage can eliminate the ongoing expenses associated with road repairs (Humphrey & Eaton, 1995). Similarly, applying TDA in basement foundations offers thermal insulation benefits, which can result in reduced heating costs over time ((Rashwan & Charette, 2105).

Figure 1.5. Damaged and uneven sidewalk due to frost heave.



Understanding TDA:
Engineering Properties & Design Considerations

2. Understanding TDA: Engineering Properties and Design Considerations

The engineering properties of tire-derived aggregate (TDA) play a crucial role in determining its suitability and performance in various civil engineering applications. Understanding these properties is essential for engineers and project managers to incorporate TDA into their designs effectively. This section explores the key characteristics of TDA, including its physical, mechanical, and thermal properties, as well as its environmental and dynamic features. By examining these aspects, we aim to provide a thorough understanding of how TDA can be utilized to enhance the durability, stability, and overall efficiency of construction projects.

2.1 Geotechnical Properties of TDA

Due to its unique geotechnical properties, TDA provides many solutions to geotechnical challenges. The following section provides an overview of this innovative material's unique geotechnical characteristics.

2.1.1 Unit Weight

TDA offers several significant technical advantages as a lightweight fill material in construction, primarily due to its low specific gravity of only 1.1 to 1.3 compared to a typical range of 2.65–2.80 for soils, leading to considerable financial savings and economic benefits (Humphrey, 2007); El Naggar & Iranikhah, 2021; Zahran & El Naggar, 2020). With a dry unit weight of just 6 and 8 kN/m^3, TDA serves as an effective substitute for conventional, denser aggregates, which typically range from 18 to 22 kN/m^3 (El Naggar et al., 2016; Humphrey et al., 1992). This weight difference not only reduces the load on underlying structures and soils but also lowers transportation and material costs, as mentioned previously, making TDA a cost-effective and practical alternative for various civil engineering projects.

When TDA is mixed with soil, the resulting composite material retains some of the benefits of reduced weight, though the exact unit weight varies with the TDA-to-soil ratio. For instance, a 50/50 TDA-soil mixture typically exhibits a unit weight of around 12 to 15 kN/m^3, which remains lighter than pure soil or gravel (Ghaaowd et al., 2017). This reduced weight is advantageous in applications such as embankment fills, retaining wall backfills, and other construction scenarios where minimizing load is crucial.

2.1.2 Compaction and Voids Ratio

Compaction and voids ratio are critical factors in determining the suitability and performance of tire-derived aggregates in various civil engineering applications. Compaction refers to the process of densifying the TDA to reduce air voids, which enhances its load-bearing capacity and stability. Due to the unique shape and elasticity of TDA particles, achieving optimal compaction requires specific techniques. However, it can be easily spread and compacted using readily available and commonly used construction equipment such as bulldozers and standard 10-ton rollers.

According to ASTM D6270 guidelines, TDA should be laid down in 300 mm layers, and each layer should be compacted by making at least six passes with the roller. It's important to note that standard methods for measuring in-place density, such as the sand cone and the nuclear gauge tests, are ineffective with TDA. Instead, the in-place density can be estimated by measuring the volume of the filled area and knowing the total weight of the TDA used.

When properly compacted, TDA demonstrates impressive load distribution characteristics, making it ideal for use in road bases, embankments, and retaining wall backfills. The voids ratio, which is the volume of voids over the volume of solids, is an essential parameter influencing the drainage properties and thermal insulation capabilities of TDA. Typically, TDA has a higher voids ratio compared to conventional aggregates, allowing for superior water drainage and reduced hydrostatic pressure in applications such as landfill drainage layers and stormwater management systems. However, this high voids ratio can also pose challenges, such as the potential for differential settlement if not properly accounted for in the design phase. Balancing compaction and voids ratio is crucial for maximizing the benefits of TDA while mitigating potential issues, thereby ensuring long-term performance and reliability where it is utilized.

2.1.3 Shear Strength of TDA

Tire-derived aggregate exhibits adequate shear strength characteristics, making it advantageous in various geotechnical applications. Shear strength is essential for the stability and effectiveness of construction materials under load. TDA features a unique blend of high elasticity and internal friction. This combination results in a material that provides adequate structural support and excellent straining capabilities. The interlocking nature of the shredded tire pieces enhances its shear strength, ensuring stability even under substantial loads in a wide range of applications.

Available research shows that the shear strength of TDA is affected by factors such as size, shape, and the level of compaction (El Naggar & Iranikhah, 2021; Strenk et al., 2007; Zahran & El Naggar, 2020a). Larger TDA pieces generally offer higher shear strength due to better interlock and resistance to movement. Also, compaction increases the contact points between the pieces, further boosting shear strength.

The inclusion of TDA in TDA-soil mixtures improves the shear strength of the soil by increasing its overall frictional resistance and elasticity. This mixture exhibits improved stability and load-bearing capacity compared to soil alone. With their high elasticity, the TDA pieces distribute stresses more effectively, reducing the likelihood of deformation under load. Additionally, the interlocking nature of the shredded tire pieces within the soil matrix enhances the overall cohesion and stability of the mixture. The shear strength of TDA/soil mixtures is influenced by the proportion of TDA added, the type of soil, and the degree of compaction. Higher ratios of TDA generally lead to increased shear strength, provided the mixture maintains adequate soil content to ensure proper compaction. The type of soil also plays a significant role, with sandy soils often benefiting more from the addition of TDA than clayey soils. Compaction is crucial as it maximizes the contact points between TDA and soil particles, further enhancing the mixture shear resistance.

Over the last few decades, several researchers have studied the shear strength parameters of TDA and its mixtures with soil. They found that the internal friction angle and cohesion of these materials range from 19° to 55° and 0 to 25 kPa, respectively (Ashari & El Naggar, 2018; El Naggar et al., 2016; El Naggar & Iranikhah, 2021; Foose et al., 1996; D. N. Humphrey et al., 1993; Sparkes et al., 2019; Wu et al., 1997). Variations in these values across different studies can be attributed to differences in testing apparatus, the source of the TDA, and the specific conditions under which the tests were conducted. Among the methods used to assess the shear strength of TDA, the direct shear test stands out. It is widely regarded in many labs as the go-to test for soil evaluation because of its straightforward methodology and reasonable accuracy. Table 2.1 summarizes typical shear strength parameters of TDA and TDA/soil mixtures as reported by different researchers.

Table 2.1: Typical shear strength parameters of TDA and TDA/soil mixtures as reported by different researchers

Materials	Size (mm)	Unit weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)	Optimum TDA content (%)	Reference
TDA	13-76	6.06-6.30	7.7-11.5	19-25	-	Humphrey & Sandford (1993)
TDA	2 - 38	4.9 – 5.9	-	44 - 56	-	Wu et al. (1997)
TDA	12 - 38	6.3 – 7.25	*16.4*	*22*	-	Zahran & El Naggar (2020b)
TDA	13 - 38	6.97 ± 0.35	*@5%strain* 10.5 @10% *strain* 18.5 @15% *strain* 25	*@5%strain* 18.5 @10% *strain* 14 @15% *strain* 23.1	-	El Naggar et al. (2022)
TDA – sand mixtures	12.7 - 25.4	*TDA* 6.13 – 6.87 *Sand* 18.18 *TDA-sand (38%)* 13.95	*TDA* *@5%strain* 13.38 - 17.10 @10% *strain* 22.13 - 24.61	*TDA* *@5%strain* 6.89 – 9.79 @10% *strain* 11.24 – 14.63	38	Ahmed (1993)
TDA – sand mixtures	50-150	*Sand* Loose:15.5 Dense:17.7 *TDA-sand* 14.7-16.8	TDA 3	*TDA* 30 *Sand* Loose:25 Dense:34 *TDA-sand* 36-67	30	Foose et al. (1996)

Table 2.1: Typical shear strength parameters of TDA and TDA/soil mixtures as reported by different researchers (cont'd)

Materials	Size (mm)	Unit weight (kN/m^3)	Cohesion (kPa)	Friction Angle (°)	Optimum TDA content (%)	Reference
TDA - clean sand and TDA-sandy silt mixtures	30-110	*TDA* 5.9 *Sand* Loose:14.7 Dense:16.8 *Sandy silt* 18.3 *TDA-sand* 13.3-15.6 *TDA-sandy silt* 16.3-17.6	*TDA* 0 *Sand* 2 *Sandy silt* 11 *TDA-sand* 2 *TDA-sandy silt* 8-39	*TDA* 30 *Sand* 34 *Sandy silt* 30 *TDA-sand* 46-52 *TDA-sandy silt* 53-55	30	Tatlisoz et al. (1997)
TDA - sand mixtures	<16	*TDA* 6.72 – 7.37 *Sand* 17.35 – 17.25 *TDA-sand* 12.42 – 15.23	-	*TDA-sand* 30 – 34	70	Youwai & Bergado (2003)
TDA - sand mixtures	<102	*TDA* 6.3 *Sand* 15.64 @ D_r 55% 16.21 @ D_r 75%	*TDA* 22.8 *Sand* 7.8 @ D_r 55% 3.8 @ D_r 75% *TDA-sand* 7 - 60	*TDA* 21.4 *Sand* 36.8 @ D_r 55% 41 @ D_r 75% *TDA-sand* 34.4 – 37.2	35	Zornberg et al. (2004)
TDA - sand mixtures	10 - 20	*TDA* 6.3 *Sand* 14.89 ± 0.27	*Sand* 0 *TDA-sand* 13.3 – 18.4	*Sand* 38 *TDA-sand* 39.9 – 40.1	20	Rao & Dutta (2006)

Table 2.1: Typical shear strength parameters of TDA and TDA/soil mixtures as reported by different researchers (cont'd)

Materials	Size (mm)	Unit weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)	Optimum TDA content (%)	Reference
TDA - sand mixtures	Dust: 0.3 Medium:23.5 Coarse: 48.5	*TDA* 3.32 – 6.92 *Sand* 18.25 *TDA-sand* 10.79 – 16.55		*TDA* 17.5 – 27.5 *Sand* 36.5 *TDA-sand* 27.5 - 45	15	El Naggar et al. (2016)
TDA - sand mixtures	<16	*TDA* 6.72 – 7.37 *Sand* 17.35 – 17.25 *TDA-sand* 12.42 – 15.23	-	*TDA-sand* 30 – 34	70	Youwai & Bergado (2003)
TDA - soil mixtures	<75	*TDA* 6.82 *Gravelly soil* 19.2 *Sandy soil* 16.8 *Clayey Soil* 18.4 *TDA-soil @25%* 14.77 – 15.73	*TDA* 18.2 *Gravelly soil* 24.8 *Sandy soil* 4.8 *Clayey Soil* 21.8 *TDA-soil @25%* 14.7 – 29	*TDA* 23.9 *Gravelly soil* 44 *Sandy soil* 37.1 *Clayey Soil* 18.8 *TDA-soil @25%* 25.6 – 43.9	10 - 25	El Naggar & Iranikhah (2021)

2.1.4 Compressibility and Stiffness

Understanding the compressibility and stiffness characteristics of TDA and TDA-soil mixtures is essential for their effective utilization in construction projects like embankments, retaining walls, and landfill covers. This section provides an analysis of the current knowledge on these properties, discussing the factors influencing them and the implications for engineering applications.

Compressibility refers to the degree to which a material can be compacted or reduced in volume under an applied load. For TDA, this characteristic is influenced by factors such as size, shape, and the proportion of TDA in the mixture. The compressibility of pure TDA is significantly affected by the size and shape of the tire shreds. Larger shreds tend to compress less than smaller shreds due to their higher rigidity and interlocking capabilities. Conversely, smaller pieces exhibit higher compressibility due to their ability to rearrange and fill voids more effectively under load (El Naggar et al., 2022; Moussa & El Naggar, 2023; Naggar & Zahran, 2021; Sparkes et al., 2019). Under low to moderate stress levels, TDA shows significant compression due to the rearrangement and realignment of TDA pieces. As stress increases, compressibility decreases because the pieces become densely packed, reducing further deformation (Zornberg et al., 2004).

The compressibility of TDA-soil mixtures depends on the type of soil and the proportion of TDA mixed with it. Adding TDA to soil generally increases the compressibility of the mixture due to the lower stiffness and higher deformability of TDA compared to most soils (Edil et al., 1992). Uniformly mixed TDA-soil combinations exhibit more predictable compressibility characteristics, while poorly mixed samples can show erratic behaviour due to the uneven distribution of TDA pieces (Ahmed, 1993).

Stiffness is a measure of a material's resistance to deformation under load. It is a critical property for designing and evaluating the performance of geotechnical structures. The stiffness of pure TDA, typically lower than that of conventional granular materials due to its rubbery nature, varies with particle size. Larger pieces generally exhibit higher stiffness ((Foose et al., 1996)). The stiffness of TDA can also depend on the rate of strain applied during testing. Faster loading rates tend to increase the measured stiffness, as there is less time for rearrangement and deformation ((Wu et al., 1997)).

The stiffness of TDA-soil mixtures is often a balance between the stiffness of the soil matrix and the deformability of the TDA particles. Cohesive soils mixed with TDA may exhibit reduced stiffness compared to pure soil, while granular soils may show less pronounced stiffness reduction, especially at low TDA content (Rao &

Dutta, 2006). Higher proportions of TDA in the mixture tend to lower the overall stiffness. Even small additions of TDA can significantly affect stiffness, especially in cohesive soils where the contrast between the stiffness of TDA and the soil is more pronounced (H. J. Lee & Roh, 2007). The stiffness of TDA-soil mixtures can be enhanced through proper compaction, ensuring better inter-particle contact and reducing the void ratio (Tatlisoz et al., 1998).

Several studies have investigated the compressibility and stiffness properties of TDA and TDA-soil mixtures, providing valuable insights into their behaviour under various conditions. Laboratory tests, such as compressibility tests, have shown that TDA exhibits a nonlinear compressibility response, with higher compressibility at lower stress levels. When mixed with soils, the compressibility behaviour becomes more complex and depends on the mixture composition and soil type ((Sparkes et al., 2019)). Triaxial compression tests indicate that TDA and TDA-soil mixtures exhibit strain-hardening behaviour, where stiffness increases with strain up to a certain point before plateauing. This behaviour is more pronounced in TDA-soil mixtures with lower TDA content (El Naggar et al., 2022).

Field studies on embankments constructed with TDA or TDA-soil mixtures have demonstrated that these materials can effectively reduce settlement and improve load distribution. The compressibility and stiffness data from these studies help in designing embankments with optimal performance (Mills & McGinn, 2010; Wartman et al., 2007).

The use of TDA behind retaining walls and in slope stabilization projects has shown that TDA can provide adequate support while allowing for controlled deformation, reducing the risk of sudden failure (Bosscher et al., 1997).

Understanding the compressibility and stiffness properties of TDA and TDA-soil mixtures is crucial for their effective use in geotechnical engineering. When designing load-bearing structures with TDA, engineers must account for their higher compressibility and lower stiffness compared to traditional materials. This involves using appropriate safety factors and ensuring adequate compaction and confinement (Rao & Dutta, 2006). In applications where settlement control is critical, such as in foundation beds or landfill covers, the compressibility of TDA must be carefully managed. Blending TDA with stiffer materials or soils can help achieve the desired balance between compressibility and stiffness (Foose et al., 1996). El Naggar & Ashari (2023) studied the stiffness behaviour of TDA-soil mixtures mixed with gravel and sand. A series of 33 consolidated drained triaxial tests were conducted on mixtures of sand, gravel, and TDA. The sand and gravel were used to represent fine and coarse aggregates, respectively, with varying proportions of TDA by weight. The TDA size used was similar to that typically used in many civil engineering applications, with the exception that any protruding steel belts were removed. Figures 2.1 and 2.2 show the secant modulus E_{50} for the TDA-sand mixtures and TDA gravel mixtures, respectively. In addition, based on the laboratory results, guidelines were provided to determine the necessary overbuild for achieving the desired layer thickness in each mixture, as shown in Figures 2.3 and 2.4.

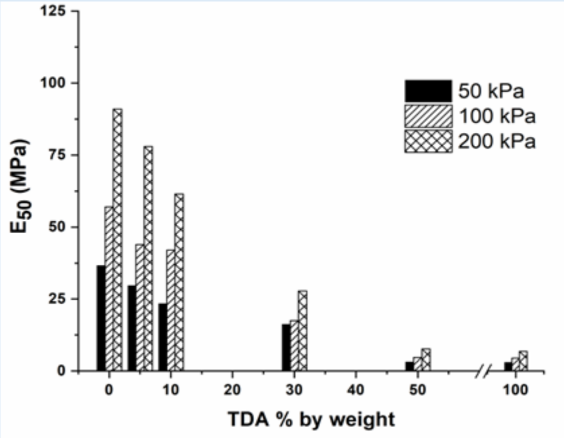


Figure 2.1: E_{50} for the considered TDA-sand mixtures at confining pressures of 50 kPa, 100 kPa, and 200 kPa.

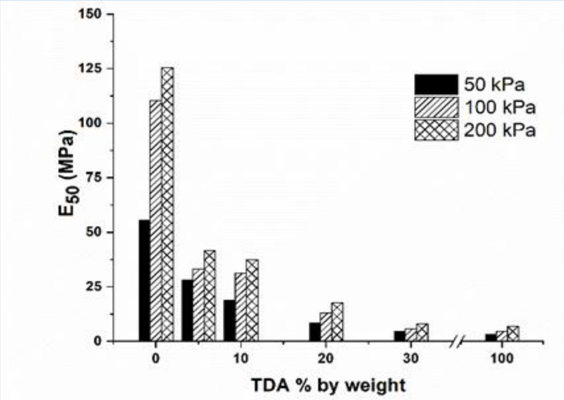


Figure 2.2: E_{50} for the considered TDA-gravel mixtures at confining pressures of 50 kPa, 100 kPa, and 200 kPa.

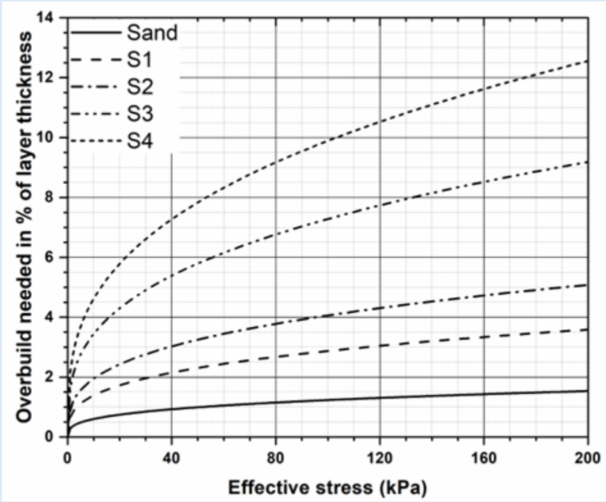


Figure 2.3: The overbuild required for TDA-sand mixtures with 0%, 5%, 10%, 30%, and 50% TDA by weight.

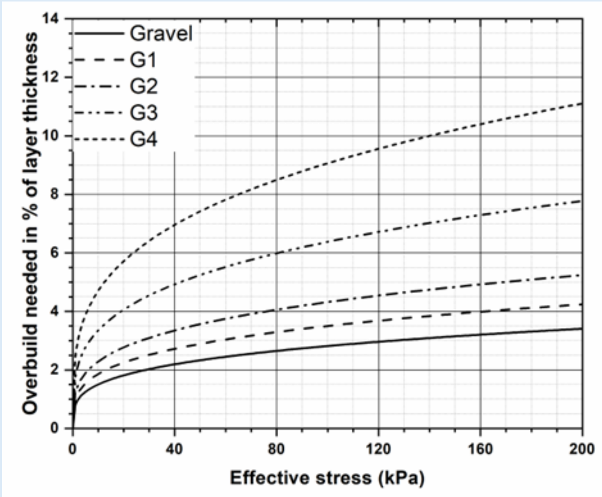


Figure 2.4: The overbuild required for TDA-gravel mixtures with 0%, 5%, 10%, 30%, and 50% TDA by weight.

Ongoing research and field studies continue to enhance our understanding of the compressibility and stiffness properties of TDA, paving the way for more widespread and effective use of TDA in sustainable engineering practices.

2.1.5 Coefficient of lateral Earth pressure

The coefficient of lateral earth pressure at rest (K_o), representing the ratio of horizontal (lateral) earth pressure to vertical earth pressure, is a critical parameter in geotechnical engineering. This parameter significantly influences the design and stability of retaining structures, slopes, and foundations. When using unconventional materials like TDA, understanding their lateral earth pressure behaviour becomes essential due to their unique properties.

Full-scale field studies by Humphrey & Sandford (1993); Tweedie et al. (1998a, 1998b) among several others have investigated the lateral earth pressure coefficient of TDA. Applying classical earth pressure theory to TDA indicates that TDA exhibits lower theoretical earth pressure at rest and active conditions compared to conventional soil. At rest earth pressure occurs when the soil mass is restrained from lateral deformation, maintaining its original stress state, whereas active earth pressure develops when the soil is allowed to deform laterally, reducing horizontal stresses due to wall movement. This difference is attributed to TDA's low unit weight and reasonable friction angle. Measurements of lateral stress under at-rest conditions, as reported by Tweedie et al. (1998a), show that the coefficient of lateral earth pressure (K_o) decreases with depth. In contrast, for granular fill, this coefficient remains approximately constant. The results of Tweedie et al. (1998) suggested that the lateral stress conditions within the TDA fill fall between at-rest and active conditions. They also concluded that the earth pressure coefficient for TDA decreases as deformation increases. This finding is supported by the shear strength results presented by (Moo-Young et al., 2003), which indicate that the friction angle increases with applied vertical load and depth, leading to a decrease in earth pressure coefficients as deformation approaches 20%.

The coefficient of lateral earth pressure for TDA can vary based on factors such as size, compaction level, and the specific application. However, it is typically lower than that of conventional soils. Various studies have provided general ranges for this coefficient, ranging from 0.26 to 0.32 for pure TDA under at-rest conditions. Likewise, (Tweedie et al., 1998b) recommend using an empirical coefficient for active pressure, K_a=0.25, for design purposes.

2.1.6 Poisson's ratio

Poisson's ratio is a fundamental material property that characterizes the elastic behaviour of a material under load. Tire-derived aggregate exhibits unique mechanical properties due to its composite nature, which includes rubber, steel, and textile fibres. The Poisson's ratio of TDA typically ranges from 0.15 to 0.30, with variations depending on the specific composition and size of the aggregate pieces. This range, which is somewhat lower than that of conventional soil and aggregate materials, usually with a Poisson's ratio between 0.25 and 0.45, is a key aspect of TDA. In practical terms, the lower Poisson's ratio of TDA can be advantageous in applications where reduced lateral expansion under load is desired, such as in retaining wall backfills and lightweight embankments. Moreover, the resilience and energy absorption properties of TDA, attributed to their rubber content, enhance their performance under dynamic loading conditions, such as in earthquake-prone areas.

2.2 Environmental Properties of TDA

The environmental properties of TDA are crucial in understanding their impact and potential benefits, which include waste reduction, resource conservation, and enhanced performance in various engineering applications.

2.2.1 Permeability and Drainage of TDA

Tire-derived aggregates exhibit superior drainage and permeability properties compared to traditional materials such as sand and gravel, primarily due to their high void ratio and porosity. This exceptional permeability makes TDA an ideal material for constructing efficient drainage systems, with hydraulic conductivity values of up to 0.51 m/s (Mwai et al., 2016). It is recommended that the hydraulic conductivity of TDA be determined based on the void ratio under field stress conditions, as it decreases with increasing stress levels (Hudson et al., 2007; Warith & Rao, 2006). Table 2.2 provides comparative data on the hydraulic conductivity of various materials. Although TDA's hydraulic conductivity decreases with increased overburden pressure, its high porosity maintains a high level of hydraulic conductivity. Even when compressed, TDA retains a hydraulic conductivity of 0.04 m/s with a porosity of 0.25, which is well above the minimum requirement of 10^{-4} m/s for landfill drainage media Hudson et al., 2007).

The permeability of TDA is significantly influenced by its high porosity, making it a highly effective material for drainage purposes. Remarkably, TDA's permeability is on par with very coarse gravel and is notably superior to other materials, being ten times higher than fine gravel, 100 times higher than wood chips, 3,000 times higher than coarse sand, and over 30,000 times higher than fine sand. These characteristics make TDA an exceptional free-draining material, suitable for a variety of applications such as drainage layers for highways, stormwater systems, daily cover layers for landfills, and subgrade support during the spring thaw. With a hydraulic conductivity of around 0.4 m/s, TDA outperforms all traditional aggregates listed in Table 2.2 in terms of drainage efficiency.

Table 2.2: Hydraulic conductivity of various materials

Rank	Material	Hydraulic conductivity m/s
1	TDA	0.03~0.51
2	Clean gravel	0.01~1
3	Expanded shale	0.04~0.6
4	Wood chips	0.024~0.084
5	Coarse sand	10^{-4}~10^{-2}
6	Fine sand	10^{-9}~10^{-5}

The exceptional permeability and drainage properties of TDA present significant advantages with few challenges. The TDA's high drainage capacity offers several benefits, including efficient water management, reduced erosion risk, and enhanced soil stability. These properties can lead to sustainable solutions in various civil engineering applications.

2.2.2 Freeze-Thaw Mitigation

Consecutive freeze and thaw cycles occur when the air temperature fluctuates between freezing and thawing, causing water to freeze and subsequently thaw repeatedly. A capillary break is a layer of material designed to prevent moisture and water movement through the microscopic fissures or capillaries present in underlying media such as soil, sand, or clay. Tire-derived aggregates provide an effective capillary break, reducing the risk of material damage caused by freeze-thaw weathering (Frascoia & Cauley, 1994; Oman, 2013).

Freeze-thaw weathering is prevalent in cold climates where ice formation occurs. When water fills cracks in soils or rocks and freezes, it expands, exerting pressure on the surrounding material. This process results in new or expanded cracks. As temperatures rise and the ice melts, these cracks are filled with water. Repeated freeze-thaw cycles cause further expansion of the cracks due to the pressure from the ice, eventually leading to the breaking of rock. The use of TDA as a capillary break to mitigate such damage has been repeatedly demonstrated.

A material with a large pore size can create a capillary break that prevents pore water from rising toward the freezing layer. TDA is an excellent option due to its high porosity, which facilitates subsurface drainage, and its hydrophobic properties that prevent water from wicking upwards through void spaces. Additionally, TDA provides superior insulation, up to eight times more than soil, further reducing the likelihood of freezing in the subsurface. The combination of TDA's high porosity and insulating power makes it an ideal material for a capillary break.

Figure 2.5 illustrates the damage caused by a capillary rise during the freeze-thaw cycle. In road construction, a geotextile fabric is typically placed below the road base and above the subgrade material. A TDA layer placed below the geotextile fabric has repeatedly been shown to enhance the capillary break (Figure 2.6) significantly.

These characteristics highlight TDA's effectiveness in mitigating freeze-thaw damage, making it a valuable material for construction projects in cold regions. By preventing water movement and providing superior insulation, TDA helps maintain the integrity and longevity of infrastructure exposed to freeze-thaw cycles.

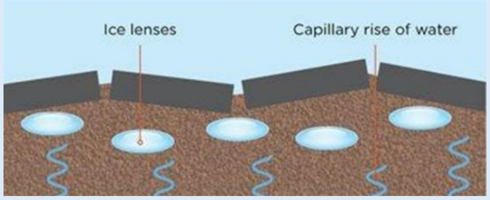


Figure 2.5: Schematic drawing of damage caused by a capillary rise during the freeze/thaw cycles. (TYPAR, 2024)

Figure 2.6: TDA layer placed below the geotextile fabric in a roadway application.

2.2.3 TDA Leaching Characteristics

End-of-life tires contain a wide range of additives, including filler systems (calcium carbonate, carbon black, clays, silicas), stabilizers (antioxidants, antiozonants, and waxes), cross-linking agents (sulfur, accelerators, and activators), and secondary components (pigments, oils, resins, and short fibers). Additionally, tires may accumulate other contaminants as a sorbent due to their exposure to various chemicals. The chemical composition of car tires encompasses diverse classes such as dithiocarbonates, guanidine, phenolics, phenylenediamines, polyaromatic hydrocarbons (PAHs), sulphur donors, sulfonamides, thiazoles, thiurams, and heavy metals. However, as discussed in the following sections, the leaching quantities of these chemicals from tires are negligible. When these leached chemicals are evaluated against regulatory limits and water-quality-based tests, they are found to pose no threat to either the ecosystem or human health.

Despite concerns regarding tire chemicals, tires' hydrophobic properties render them effective adsorbents, mitigating the migration of contaminants into the surrounding environment. Recent research by CalRecycle and others has demonstrated the benefits of using TDA in urban stormwater infiltration galleries. These studies have led to the construction of multiple infiltration gallery projects in California, which have successfully reduced peak surface water flow, captured and concentrated road surface particles, and decreased the concentration of heavy metals and other pollutants (Park, DeNooyer, et al., 2023).

Substantial evidence indicates that TDA does not cause primary drinking water standards to be exceeded for both above and below water table applications. Additionally, TDA is unlikely to elevate metal levels with primary drinking water standards above naturally occurring background levels. These characteristics significantly reduce the potential for environmental damage, underscoring the relative safety of using TDA in various applications. The subsequent sections will provide an overview of the leaching behaviour of tire-derived aggregate, highlighting its negligible environmental impact and reinforcing its suitability for sustainable engineering practices.

2.2.4 Leaching Test Methods

The Toxicity Characteristic Leaching Procedure (TCLP) is a chemical analysis process widely used to determine the concentrations of the various tire components. Researchers have utilized TCLP to assess the relative toxicity of leachate extracted from TDA (Downs et al., 1996; Ealding, 1992; Park, DeNooyer, et al., 2023). TCLP evaluates the mobility of organic and inorganic contaminants in various wastes in accordance with the Resource Conservation and Recovery Act (RCRA). This act grants the US EPA authority to manage hazardous waste from its creation to disposal. However, it is important to recognize that TCLP results should not be used to assess the environmental impact of TDA in civil engineering applications, as the test is designed to determine if samples are hazardous waste for disposal purposes.

TCLP employs a solution with an acidic pH level of less than 5 to simulate the leaching potential of waste in a landfill setting. For evaluating the environmental impact of TDA in civil engineering, leaching tests should use a pH range of 5.6 (rain) to 8. The World Health Organization (2017) and the US EPA (United States Environmental Protection Agency, 2018) recommend that drinking water should have a pH between 6.5 and 8.5 to minimize dissolved contaminants from acidic water and prevent scale buildup from alkaline water. Groundwater with a pH below 3.5 does not meet the National Secondary Drinking Water Regulations (NSDWRs), regardless of zinc levels exceeding Secondary Maximum Contaminant Levels (SMCLs) (Han, 1998). Therefore, when approving TDA for civil engineering applications, it is crucial to carefully evaluate analytical results, regulations, and site conditions. Based on TCLP toxicity standards, regulatory limits for any target elements were not exceeded, and TDA was not classified as hazardous waste (Cheng, 2016).

2.2.5 TDA Leaching and the Environment

Chemicals used in tire manufacturing can leach into the environment in gas, solid, and liquid forms. Organic compounds may volatilize and enter the atmosphere, but their health effects are generally minimal due to the slow rates of volatilization and rapid dilution unless tires are stored in confined spaces. Tire road wear particles reportedly represent one of the largest sources of microplastic contamination (Rødland et al., 2022). These particles increase the surface area of tires, accelerating chemical leaching. Therefore, implementing stormwater management systems is crucial to reduce microplastic and water contamination.

A primary concern with the use of tire-derived aggregates is the leaching of tire components into water. The concentration of these components from end-of-life tires, after exposure to groundwater or rainwater, is influenced by factors such as pH, temperature, tire size (Selbes et al., 2015) and contact time. This indicates that TDA used in civil engineering applications has a much lower environmental impact than crumb rubber.

Tire wear particles and crumb rubber, often exposed to ultraviolet (UV) light and rainwater, have a higher leaching potential compared to TDA and whole tires. Unlike tire wear particles, crumb rubber used in athletic fields, tire chips in playgrounds, and open-dumped whole tires, TDA is used underground, covered by geotextile, gravel, and asphalt. When whole tires are exposed to UV light and rainwater, they may leach components and byproducts, such as 6-PPD-Quinone. Consequently, TDA is expected to have the least environmental impact because it is buried underground. When tire components leach, they interact with various media, such as soil, water, and organics found in these environments. These interactions lead to processes like biodegradation, abiotic degradation, volatilization, and adsorption. However, as all TDA-implemented projects are located underground, concerns related to ultraviolet exposure and human contact, as well as issues often associated with other forms of end-of-life tires, are eliminated.

Metals such as Zn, Fe, Mn, Cu, Co, Cr, Pb, and Ni have been detected in leachate. When steel wire in TDA is exposed, Fe and Mn concentrations in groundwater are likely to increase, while Al and Zn typically remain at negligible levels. However, these concentrations typically attenuate to near-background levels after migrating a short distance through the surrounding soil. For other constituents regulated by secondary drinking water standards, there is no evidence that TDA alters naturally occurring background concentrations (D. N. Humphrey & Swett, 2006). TDA is primarily used in civil engineering in uncontaminated areas, except when it is employed to adsorb and react with inorganic and organic contaminants. Therefore, test results that exceed the National Drinking Water Regulations (NDWRs) Maximum Contaminant Levels (MCLs) and Secondary Maximum Contaminant Levels (SMCLs) should be disregarded if the water is already contaminated.

Once tire components leach out, they encounter two conditions: water percolating through tires and tires in the waterbody. Under unsaturated conditions, repeated dry-wet cycles leach more heavy metals compared to saturated conditions ((Maeda & Finney, 2018)). However, increased soil porosity results in less leaching due to shorter contact time, though the mobility of leachate increases. In saturated conditions, the longer contact time results in higher concentrations of leached tire components. Metals can exchange with, precipitate, or adsorb to other inorganic materials in soils. Most leached organic components either biodegrade to CO_2 or other byproducts, adsorb to soil matrices, or persist in the environment (Park & Ye, 2016).

Various factors, including pH, particle size, and the solid-to-liquid (S/L) ratio, impact the leaching of tire components (Gualtieri et al., 2005; Kanematsu et al., 2009; Rhodes et al., 2012; Wik et al., 2009). Selbes et al. (2015) found that the size of processed scrap tires significantly affects chemical leaching from end-of-life tires. However, for TDA, the leaching of inorganic constituents such as S, Zn, Cd, Cr, As, K, P, Na, Mn, Fe, Ca, Mg, Al, Cu, Pb, Se, Mo, and Ni is negligible. Several researchers reported the results of numerous tests conducted to evaluate metal leaching from tires of various sizes, with concentrations ranging from undetectable levels to approximately 10,000 mg/L. According to Jeong (2022) Zinc (Zn) exhibited the highest concentration among metals in all tested tire samples. The average concentrations of metals were found in the following descending order: Zn, Cu, Pb, Sn, Sb, Ni, Cr, As, and Cd.

Table 2.3 compares metal concentrations in soils and tires. The analysis reveals that, apart from zinc, the concentrations of most metals in soils are higher than those in tires.

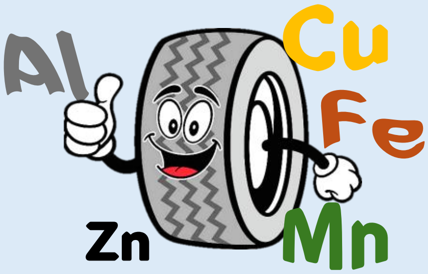


Table 2.3 The range of metals in soils and tires (McLean & Bledsoe, 1992).

Metal	Soils (mg/kg)	Tires (mg/kg)
Al	10,000~30,000	81~420
Fe	7,000~55,000	2.12~533
Mn	20~3,000	2
Cu	2~100	1.8-29.3
Zn	10~300	8,378-13,494
Pb	2~200	1~160

Consequently, the leaching of metals from tires is generally not considered a significant environmental concern. Hence, in stormwater management systems that incorporate TDA, the environmental impact is expected to be comparable to or better than that of traditional systems using conventional natural materials. This indicates that TDA is a safe and reliable material for civil engineering applications, as it does not significantly release potentially hazardous compounds into the environment. Nevertheless, to mitigate potential concerns about metal leaching from TDA, it is advisable to include a soil buffer layer of 2 to 10 feet (0.6 to 3 meters).

2.2.6 Impact of Leached Tire Components on Groundwater Quality

The use of tire-derived aggregate has been found to have a negligible effect on groundwater quality. This section summarizes key findings from various studies examining TDA's influence on groundwater, focusing on parameters such as hardness, total organic carbon (TOC), total organic halides (TOX), and specific conductance. These metrics help assess water quality and the potential risks associated with TDA use.

The National Secondary Drinking Water Regulations (NSDWRs) provide non-enforceable guidelines for contaminants affecting water's aesthetic qualities, including taste, odour, and colour. In contrast, enforceable MCLs address contaminants that pose significant health risks, such as bacteria, viruses, and certain chemicals. Study results are evaluated by comparing them against US EPA regulatory standards.

2.2.6.1 Hardness and PH

Water hardness can impact both taste and appearance. Hoppe & Mullen (2004) found no significant change in hardness due to TDA in their study, with the control well showing an average of 24.60 mg $CaCO_3$/L and the test well 23.98 mg $CaCO_3$/L. The MCL for pH ranges between 6.5 and 8.5, yet the control well's pH averaged 4.82, and the test well's pH averaged 4.30. The confidence level for pH change between wells was closer to 95%, indicating no statistically significant difference. Likewise, Humphrey & Swett (2006) found no significant change in their results due to the presence of TDA. Literature suggests iron and zinc levels might increase in acidic conditions (pH < 7), however, observed levels in the study were lower than expected. Edil (2008) noted an increase in hardness over time, though none of the tested elements (As, Ba, Ca, Cd, Cr, Co, Cu, Fe, Pb, Mg, Mn, Mo, Ni, Se, Na, Zn) exceeded Wisconsin's Preventive Action Limits (PALs).

2.2.6.2 Total and Dissolved Organic Carbon (TOC and DOC)

TOC measures the amount of organic matter in water, where higher levels can indicate microbial or bacterial presence, affecting water safety. The TOC MCL is 2.0 mg/L. The control well averaged 1.62 mg/L, while the test well averaged 1.0 mg/L, based on 32 samples per well, with 16 non-detects in the control and 28 in the test well. No significant TOC increase was linked to TDA (Hoppe & Mullen, 2004). Selbes (2009) found crumb rubber and tire chips leached DOC at ~12 and 2.7 mg/kg tire, respectively, and Edil (2008) observed a TOC increase of 150-220 mg/kg tire in a year-long laboratory test.

2.2.6.3 Total Organic Halides (TOXs)

TOXs, which can indicate pollution, pose health risks at high levels, though they have no set MCL. The control well averaged 0.033 mg/L, and the test well was 0.30 mg/L across 32 samples each, with 24 non-detects in the control and 28 in the test well. No significant TOX increase was attributed to TDA ((Hoppe & Mullen, 2004)).

2.2.6.4 Specific Conductance

Specific conductance measures water's ionic activity and dissolved solids content, with an MCL of 1,600 mhos/cm^2. The control well averaged 143.9 mhos/cm^2, while the test well averaged 135.6 mhos/cm^2. No significant change in specific conductance due to TDA was detected (Hoppe & Mullen, 2004). Similarly, Maeda & Finney (2018) reported that TDA is unlikely to affect specific conductance or concentrations of nitrate, oil, grease, and sulfate in leachate (Maeda & Finney (2018)).

2.2.7 Impact of Leached Tire Components on Aquatic Species

Evaluating the impact of chemicals leached from tires on aquatic species and human health is a significant concern. It's crucial to understand their toxicity so that appropriate safety measures can be implemented clearly. Gualtieri et al. (2005) found that tire wear leachates were significantly less toxic than other rubber samples in their test. This indicates that tire wear leachates pose a lower environmental risk compared to other rubber types. Wanielista et al. (2008) conducted toxicity tests using tire crumbs and fathead minnows, concluding that tire crumbs were non-toxic when tested in tap and distilled water. Interestingly, tire crumb filtrate increased the minnows' survival rates compared to control chambers, although the presence of tire crumbs in detention ponds reduced their survival rates.

Maeda and Finney (2018) discovered that using Tire-Derived Aggregate (TDA) as fill material saturated with water did not harm water quality in surrounding areas. Their research showed that a TDA-soil system could effectively remove pollutants such as iron, manganese, zinc, cadmium, methyl isobutyl ketone, benzene, and phosphate from stormwater runoff. The metal concentration in the leachate depends on the amount of exposed and free metal in the TDA. Overall, TDA fills that are seasonally or always saturated are unlikely to degrade water quality. This suggests that TDA could be a sustainable alternative to traditional fill materials like gravel or sand for stormwater management, potentially reducing groundwater pollution and offering a cost-effective solution. However, more research is needed to evaluate the long-term environmental impact of TDA on groundwater quality, although initial findings are promising (Maeda and Finney, 2018). Similarly, Halsband et al. (2020) studied tire crumb rubber leaching in marine environments, finding that toxicology studies on tire wear particles (TWP) and crumb rubber granulate (CRG) varied widely due to differences in tire composition, leachate generation methods, and species sensitivity (Wagner et al., 2018; Wik & Dave, 2009). The specific components causing toxicological responses in aquatic environments are not yet fully understood. Standardizing methods for generating leachates, characterizing chemical compositions, and measuring hazard potential are necessary to compare CRG/TWP toxicity data effectively. Existing guidelines on soluble contaminants might be adjusted to create a leachate guideline, and methods should be developed to differentiate between particle effects and additive chemical effects (Halle et al., 2020; Wagner et al., 2018; Wik & Dave, 2009).

The US EPA's Federal Research Action Plan (FRAP) on tire crumb rubber characterization suggests limited human exposure to chemicals in tire crumb rubber when released into the air or simulated biological fluids (Thomas et al., 2019). Trace amounts of metals were released into simulated biological fluids, and emissions of many organic chemicals into the atmosphere were below detection limits or test chamber background levels. These findings indicate a lower health risk from metal exposure in crumb rubber than previously thought. The study noted the presence of bacteria in all crumb rubber samples, which could pose a health risk. It is important to consider that releasing metals into simulated biological fluids is just one aspect of the overall risk assessment, and other potential health risks associated with tire crumb rubber exposure may still exist.

p-Phenylenediamines (PPDs), widely used in the rubber industry, have been prevalent in various environmental compartments for decades. PPDs react highly with ozone, producing 6-PPD quinone (6-PPDQ) as the dominant byproduct ((Seiwert et al., 2022)). Cao et al. (2022) found five quinones originating from PPDs to be common in urban runoff, roadside soils, and air particles. 6-PPDQ was toxic to coho salmon but less so to chum salmon (Hiki et al., 2021; McIntyre et al., 2021). PPDs leached from TDA were much lower than from tire wear particles, and 6-PPDQ was not toxic to other fish. Since TDA is primarily used underground, the formation of 6-PPDQ is less likely in civil engineering projects, suggesting that TDA and filter layers, including soil matrices, can remove PPDs and 6-PPDQ from tire wear particles and dissolved runoff.

In conclusion, the leached components from TDA are unlikely to cause serious ecological and human health issues due to their low concentrations. Moreover, TDA can adsorb contaminants, provide favourable surfaces for microbial growth, and promote anaerobic dehalogenation, further reducing environmental risks.

2.3 Dynamic Properties of TDA

Several studies have demonstrated the effectiveness of tire-derived aggregate in various civil engineering applications under dynamic loading conditions due to their low unit weight, extensive elastic range, and superior damping capacity. Hafez et al. (2013) demonstrated that integrating TDA around a box culvert effectively reduced the seismic demands on the structure. Similarly, research by Ahn and Cheng (2014) indicated that TDA improved the seismic performance of retaining walls. Likewise, M. Xiao et al. (2012) showed that mechanically stabilized earth walls with TDA backfill performed better under seismic conditions compared to those using natural soil. Furthermore, a comprehensive finite element analysis by Ahn & Cheng (2017) revealed that TDA backfill significantly decreased acceleration amplification at the surface of a semi-gravity-reinforced concrete cantilever retaining wall. In another application, Ni et al. (2018) found that the inclusion of TDA enhanced the structural performance of buried pipelines at fault crossings by approximately 20%. Moreover, Kaneko et al. (2013) demonstrated through pseudo-dynamic response analysis that a soil layer consisting of pure rubber or a soil-rubber mixture substantially reduced ground surface accelerations and improved seismic isolation due to its damping properties. Likewise, Ahn and Cheng (2014), Jafari (2016), and Gromysz & Kowalska (2017) emphasized the effectiveness of TDA in seismic isolation and vibration damping.

In this section, the dynamic response and characteristics of TDA are explored using large-scale cyclic triaxial tests, cyclic simple shear tests, and bender element tests. Additionally, various critical factors influencing the behaviour of TDA are presented and discussed, including the TDA size, specimen size, loading rate, number of cycles, effect of saturation, and drainage conditions. Understanding the impact of these factors on the TDA's dynamic response is essential for effective dynamic design using this new geomaterial. Additionally, a shear modulus degradation model for TDA is presented. This model, along with the presented TDA's dynamic properties, is vital for civil engineering practitioners, particularly in applications related to seismic isolation and vibration mitigation.

2.3.1 Key TDA Dynamic Parameters

Key dynamic parameters such as the shear modulus and damping ratio variations with shear strain amplitudes are essential for the dynamic design. Feng & Sutter (2000) investigated the shear modulus degradation and damping ratios of various rubber/soil mixtures and pure rubber using a cyclic torsional resonant column. The rubber particles used were small, ranging from 2 to 4.76 mm. The study considered confining pressures between 69 and 483 kPa and shear strain amplitudes from 0.0003% to 0.1%. the reported results indicated an increase in shear modulus with rising confining pressure, whereas damping ratios remained unaffected by changes in the confining pressure. The measured shear modulus and damping ratios ranged from 1180 to 2800 kPa and 4.5% to 6%, respectively. Likewise, Hazarika et al. (2010) explored the cyclic behaviour of tire chips and sand-tire chip mixtures using undrained cyclic triaxial tests. Similar to Feng & Sutter (2000), the particle size of the tire chips was small, with a maximum size of 1 mm. The hysteretic stress-strain curves derived for tire chips demonstrated clear viscoelastic behaviour with minimal stiffness reduction per cycle and no excess pore water pressure, indicating the ability of tire chips to control or prevent liquefaction. Kaneko et al. (2013) confirmed these findings, attributing the prevention of excess water pressure buildup to the high deformability of tire chips.

Madhusudhan et al. (2017) investigated the cyclic behaviour of TDA and TDA-soil mixtures using a maximum TDA particle size of 2 mm. Strain-controlled undrained cyclic triaxial tests were performed under a confining pressure of 100 kPa and a shear strain amplitude range of 0.07% to 1.3%. Shear modulus values and damping ratios varied from 1000 kPa to 2250 kPa and from 10% to 11%, respectively, with damping ratios showing minimal sensitivity to increasing shear strain.

The aforementioned studies focused on TDA sizes ranging from 1 mm to 4.76 mm, which are not typical for civil construction applications. Nevertheless, Lee et al. (2010) suggested that TDA sizes between 1 to 7 mm are optimal for TDA-soil mixtures to achieve uniformity under dynamic loads. Addressing this size limitation, Moussa et al. (2023), Moussa & El Naggar (2023, 2024), and McCartney et al. (2017) conducted large-scale cyclic triaxial and simple shear tests on Types A and B TDA with maximum aggregate sizes ranging from 25 mm to 320 mm, respectively.

These studies aimed to comprehensively characterize the dynamic properties of TDA with large aggregate sizes. These studies assessed the variation of shear modulus and damping ratios with shear strain amplitudes ranging from 0.1% to 10% under confining pressures ranging from 25 to 200 kPa.

The shear modulus of Type A TDA has a range of 245 to 1796 kPa, with a decreasing trend with increasing shear strain amplitudes. Furthermore, the dampening ratios were found to be ranging from 11% to 23.5%. whereas the shear modulus of Type B TDA ranged from 155 to 2386 kPa, aligning with the values reported by previous studies, while the damping ratio at 0.1% shear strain ranged from 21 to 26.8%, highlighting TDA's significant damping capacity compared to granular soils.

While the loading frequency, drainage condition, anisotropy, shear strain amplitude, and vertical stress strongly influenced the shear modulus of TDA, these testing parameters had little or no effect on the damping ratios of TDA specimens.

2.3.2 Shear Modulus Reduction Curves

Moussa & El Naggar (2021)modified the nonlinear hyperbolic stress-strain model originally developed by Kondner & Zelasko (1963) and was improved later by Duncan & Chang (1970) to estimate the small strain shear modulus G_{max}. The proposed generalized MKZ model for TDA by Moussa

& El Naggar (2021) can be written as follows:

$$G/G_{max} = \left[\frac{1}{1+((0.0022\sigma_c+1.97)\,\gamma)^{(-0.001\sigma_c+0.62)}}\right]$$

where, G_{max} is the maximum shear modulus, σ_c is the confining pressure, and γ is the shear strain.

Figures 2.7 and 2.8 show typical shear modulus reduction curves for Type A and Type B TDA, respectively, at different confining pressures. Similarly, Figures 2.9 and 2.10 show their damping variations.

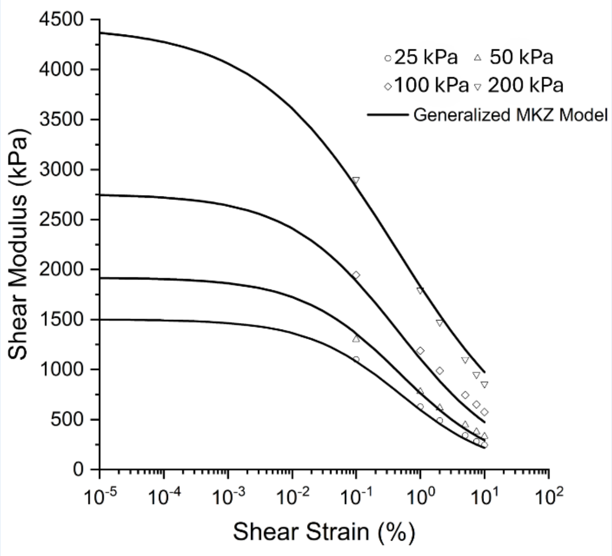


Figure 2.7: Shear modulus degradation curves for Type A TDA at different confining pressures. (After Moussa & El Naggar (2021)

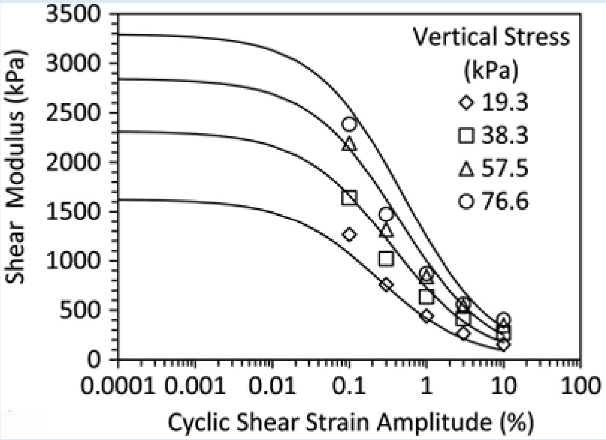
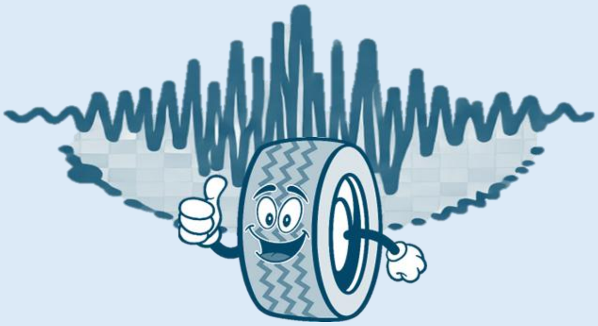


Figure 2.8: Shear modulus degradation curves for Type A TDA at different confining pressures. (After McCartney et al., 2017)



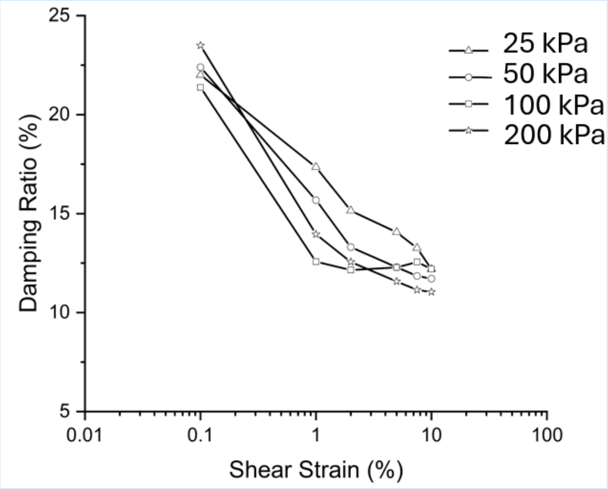


Figure 2.9: Damping curves for Type A TDA at different confining pressures. (After Moussa and El Naggar, 2021)

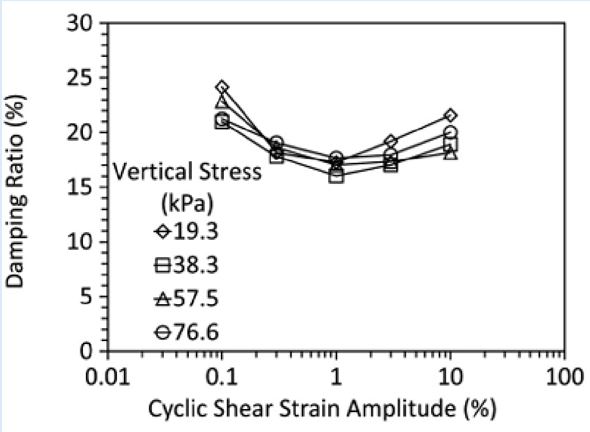


Figure 2.10: Damping curves for Type B TDA at different confining pressures. (After McCartney et al., 2017)

2.4 Thermal Properties of TDA

TDA is emerging as a versatile material in different civil engineering applications, as discussed earlier, due to its unique properties and environmental benefits. One critical aspect of TDA that has garnered significant interest is its thermal properties. Understanding the thermal characteristics of TDA is crucial for its effective application in various civil engineering projects, including road construction, embankments, insulation layers, and landfill covers.

This section explores the thermal properties of TDA, including its thermal conductivity, specific heat capacity, and its behaviour under different environmental conditions.

2.4.1 Thermal Conductivity

Thermal conductivity is a critical property that measures a material's ability to conduct heat. Materials with high thermal conductivity transfer heat more rapidly than those with low thermal conductivity. This property is especially important in designing thermal insulation systems, such as those used for buried pipelines in permafrost regions and energy storage systems. TDA generally exhibit lower thermal conductivity compared to conventional construction materials such as soils and aggregates, positioning them as effective thermal insulators.

Extensive research has been conducted to evaluate the thermal conductivity of TDA under various conditions. Bosscher et al. (1997) studied the thermal properties of shredded tires, discovering that the TDA's thermal conductivity is significantly lower than that of typical soil materials. Their findings suggested that incorporating TDA into embankments could provide thermal insulation, which is beneficial in regions with extreme temperatures. Similarly, Humphrey et al. (1998) explored the thermal properties of tire chips used as lightweight fill material, concluding that TDA's low thermal conductivity offers thermal benefits in applications such as insulating backfill for foundations and utility trenches. Further research focused on using TDA in landfill cover systems found that TDA's low thermal conductivity reduces heat flow into waste masses, minimizing the production of landfill gas and leachate. This property enhances the stability and environmental safety of landfill sites.

Based on the conducted research, the typical range of thermal conductivity for TDA lies in the range of 0.15 to 0.25 W/mK, while soil ranges from 0.25 to 1.5 W/mK, depending on moisture content and density (Foose et al., 1996; Bosscher et al., 1997; Humphrey et al., 1997; Y. Xiao et al., 2019). The low thermal conductivity of TDA can be attributed to its composition and structure, which is primarily composed of rubber, which inherently has low thermal conductivity. Additionally, the presence of air voids within the aggregate further decreases its heat transfer capability. These air pockets act as thermal insulators, significantly lowering the overall thermal conductivity of TDA.

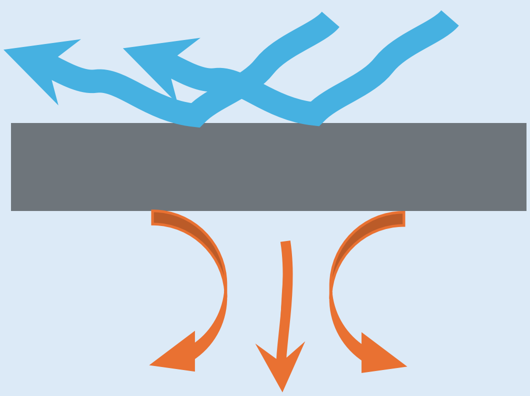
Factors such as size, shape, and compaction level significantly influence the thermal conductivity of TDA. Lawrence et al. (1999) demonstrated that the apparent thermal conductivity of Type A TDA, with a maximum size range of 38 mm to 76 mm, decreases as density increases. Additionally, when controlling for density, they found that TDA made from steel-belted tires exhibited higher thermal conductivity than TDA from glass-belted tires. However, TDA made primarily from steel-belted tires is more relevant for civil engineering applications since glass-belted tires are typically allocated to higher-value end uses.

Shao et al. (1995) investigating crumb rubber with particle sizes of 0.1 to 25 mm observed that thermal conductivity increases with larger particle sizes, higher water content, and greater density—findings that diverge from Lawrence et al.'s study. This discrepancy is likely due to more pronounced thermal convection in the air voids of larger-size TDA at lower densities. Supporting this, Humphrey et al., (1997) used field measurements to back-calculate the apparent thermal conductivity of Type A TDA, reporting a value of approximately 0.20 W/m/°C.

2.4.2 Specific Heat Capacity

Specific heat capacity, also called mass heat capacity, refers to the amount of heat required to raise the temperature of a unit mass of material by one degree Celsius. For tire-derived aggregates, this thermal property is crucial in determining their performance across various applications.

Numerous studies have explored the thermal properties of TDA, focusing primarily on their specific heat capacity. Bosscher et al. (1997) conducted a significant study that emphasized the potential of TDA for highway embankments, noting the importance of their thermal properties as mentioned earlier. They measured the specific heat capacity of TDA using calorimetric methods and found it to range between 1.1 and 1.3 J/g°C. This relatively high range compared to traditional aggregates makes TDA suitable for applications requiring good thermal insulation properties. Humphrey & Katz (2001) also investigated the specific heat capacity of tire chips used in landfill drainage systems, reporting a value of approximately 1.2 J/g°C. This indicates that TDA can absorb and retain a significant amount of heat, which is beneficial in mitigating temperature fluctuations in landfill liners and other applications where thermal stability is crucial. For instance, in pavement systems, TDA can help moderate temperature extremes, reducing thermal stresses and potential cracking in the asphalt layer above. By acting as a thermal buffer, TDA absorbs heat during the day and releases it at night, reducing thermal gradients and the associated damage. Similarly, in landfill applications, TDA's heat storage capacity can maintain stable temperatures within the landfill cover, enhancing landfill gas collection efficiency and improving waste decomposition rates.



It is important to note that the specific heat capacity of TDA is influenced by its rubber content and the presence of steel belts and bead wire. Rubber, the primary component of TDA, significantly impacts its overall thermal properties. As an organic polymer, rubber has a relatively high specific heat capacity compared to materials commonly used in civil construction, such as soils and aggregates. The rubber content in TDA varies depending on the source and processing of the tire material, with higher rubber content generally increasing the specific heat capacity of TDA because rubber can store more thermal energy per unit mass. Additionally, TDA contains steel fibres, remnants of the steel belts and wires used in tires. These fibres alter the thermal properties of TDA in several ways. Steel, having a much lower specific heat capacity than rubber but being highly conductive, can create a composite material with enhanced thermal conductivity when included in TDA. This can lead to faster heat dissipation, which may be beneficial or detrimental depending on the application. For example, in applications where thermal conductivity needs to be minimized to retain heat, the presence of steel fibres might be a disadvantage. Conversely, in scenarios requiring quick heat dissipation, such as in fire-resistant barriers, the increased conductivity due to steel fibres can be advantageous.

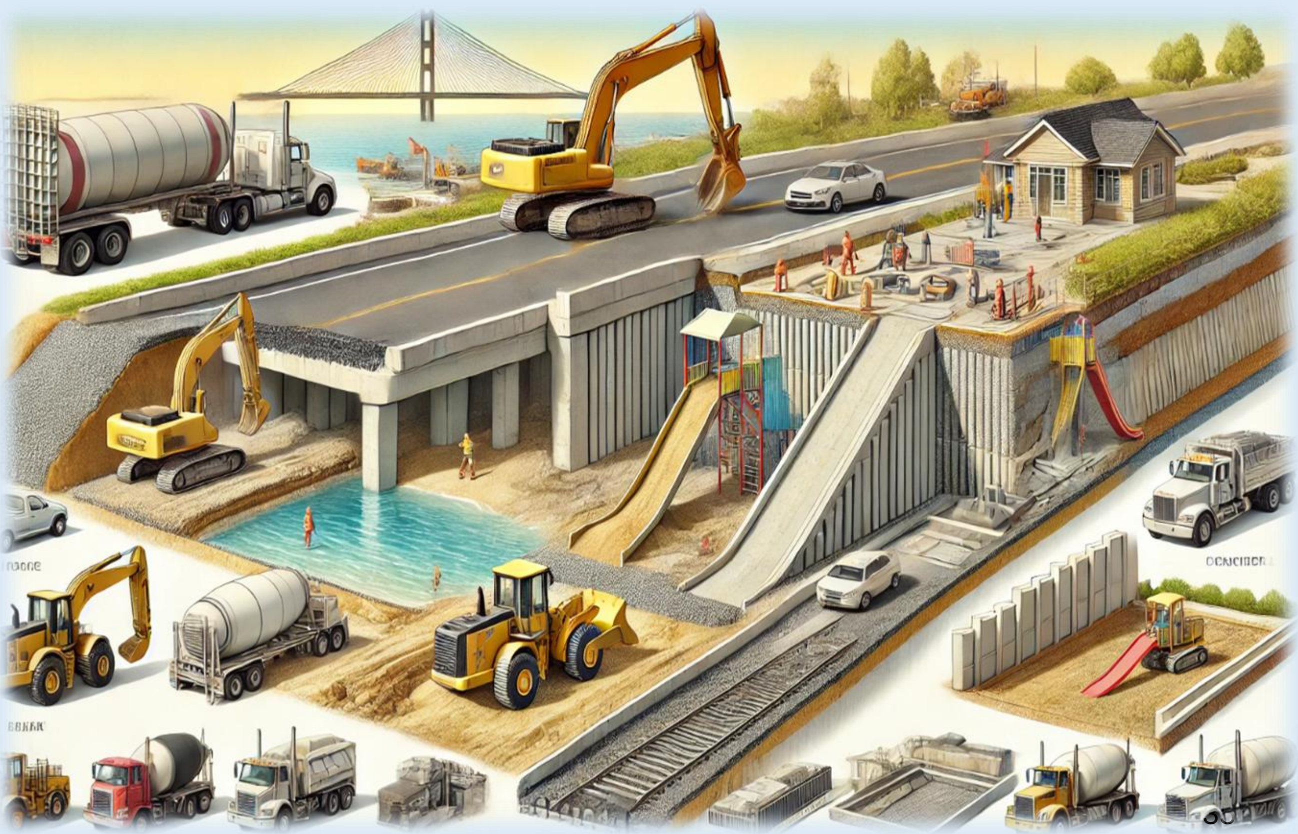
2.4.3 Self-heating of TDA

TDA can exhibit self-heating behaviour, primarily due to the exothermic corrosion of exposed steel components within the shredded tire particles (Arroyo et al., 2011). When TDA is used as fill in civil engineering projects, especially in thick layers and poorly ventilated conditions, heat can accumulate over time. The main source of this heat is the oxidation of steel belts and wires embedded in the rubber, which, in the presence of moisture and oxygen, can release significant thermal energy. Laboratory and field studies have confirmed that rainfall, ambient temperature, and the presence of fine steel wires can increase the rate of corrosion, thus elevating internal temperatures. If unchecked, these processes can lead to temperature spikes exceeding 180°C, the threshold for the thermal degradation and potential combustion of rubber materials.

To mitigate the risk of self-heating and potential spontaneous combustion in TDA fills, strict guidelines for materials and construction are implemented. These measures are based on established standards, such as those outlined by (ASTM D6270-20, 2020), and include specific constraints on both the construction process and the physical characteristics of the material. For example, the maximum allowable thickness of TDA layers is limited to 3 meters for Class II fills, while in cases where the grain size distribution does not meet specified criteria, the thickness is further restricted to 1 meter for Class I fills.

Additional construction practices are designed to reduce water and air ingress into the TDA fill, such as eliminating bottom drainage features, avoiding contact with topsoil, and incorporating physical barriers. Material quality controls are also enforced, including restrictions on metallic content—free metal fragments must comprise less than 1% of the TDA by weight. Furthermore, protruding steel elements must be kept under 50 mm in length in at least 90% of the material by weight, and under 25 mm in at least 75%. Adherence to these practices has proven effective; to date, there have been no documented cases of self-combustion in fills constructed in accordance with these specifications.

Geotechnical and GeoStructural Applications of TDA



3. Geotechnical and GeoStructural Applications of TDA

The utilization of tire-derived aggregate in civil engineering has emerged as a significant advancement in sustainable construction practices. As the world grapples with the dual challenges of managing vast quantities of End of life tires and the need for innovative construction materials, TDA offers a compelling solution. This chapter aims to explore the various applications of TDA in civil engineering projects, highlighting its benefits, challenges, and potential for broader adoption.

3.1 Embankments

3.1.1 Background

The use of tire-derived aggregates as fill material for embankments offers a sustainable and cost-effective solution in civil engineering. TDA's unique properties, including their lightweight nature, high hydraulic conductivity, and thermal insulation capabilities, provide significant advantages in embankment construction. Over the past few decades, TDA has been successfully employed as an alternative fill material to enhance the stability of numerous embankments globally.

When designing and constructing embankments with TDA, the main factors to consider are the stability and settlement of the foundation soils. These factors influence construction staging, time requirements, and potential impacts on nearby structures such as buildings, bridge foundations, and utilities. TDA is particularly advantageous for embankments built on weak soils like soft marine clays, as it helps control settlement, which is crucial for maintaining the structural integrity and safety of an embankment. TDA weighs only about one-half to one-third of conventional fill materials (see Section 2.1), reducing the vertical load on the underlying foundation soil. Consequently, areas with weak foundation soils experience less settlement and a lower risk of embankment failure (CalRecycle, 2016). Additionally, TDA's high void space makes it highly permeable (see Table 2.2), often eliminating the need for sub-drain systems and resulting in significant cost savings.

Moreover, TDA enhances slope stability along roadways, reinforces roadway shoulders, and insulates against frost penetration when used as embankment fill material. Due to these beneficial properties, TDA has gained wide acceptance as an excellent fill material for embankments (Humphrey, 2007; Meles et al., 2014; Mills et al., 2015; and El Naggar et al., 2019).

3.1.2 Design Procedures and Guidelines

To ensure the successful application of TDA in civil engineering projects:

- Determine the geotechnical properties of the soils at the site and that of the used TDA, such as density, shear strength, stiffness, and compressibility, to ensure that they meet design requirements.
- Based on the design requirements and site conditions, select the appropriate TDA gradation and quality. Complying with the specifications of ASTM D6270 and other relevant standards facilitates high-quality and consistent materials.
- The thickness of a TDA layer should not exceed 3 meters to comply with ASTM D6270.
- Calculate the volume and the number of tons of TDA required for the project using the procedure discussed in section 2.1.4, based on the design load and allowable settlement criteria.
- Proper drainage solutions must be employed in areas with high water tables to prevent moisture resurfacing and destabilizing the embankment.
- TDA should be placed on a well-draining subgrade to facilitate proper drainage and avoid water accumulation.
- TDA layers used in embankments must be fully enclosed with geotextile material on all sides – top, bottom, sides, and ends. This geotextile must meet the standards for separation to prevent soil from migrating into the TDA volume.
- Sides of TDA embankments should be covered with at least a 1 m thick layer of conventional soil.
- Soft soil conditions may require additional design measures, such as geotextiles, geogrids, or soil stabilization techniques to enhance foundation strength and stability.
- The slope of the TDA layer must be designed for stability, preventing sliding or erosion.
- The load-bearing capacity must be evaluated to support anticipated loads without experiencing any excessive settlements.
- Proper maintenance strategies, including erosion prevention and addressing any settling or deformation over time, are crucial.

By carefully considering these factors and adhering to established guidelines, engineers and designers can effectively implement TDA in embankment projects. This results in structures that are not only stable and durable but also environmentally friendly. Figures 3.1 to 3.4 present sample cross-sections of embankment projects in Canada and the United States.

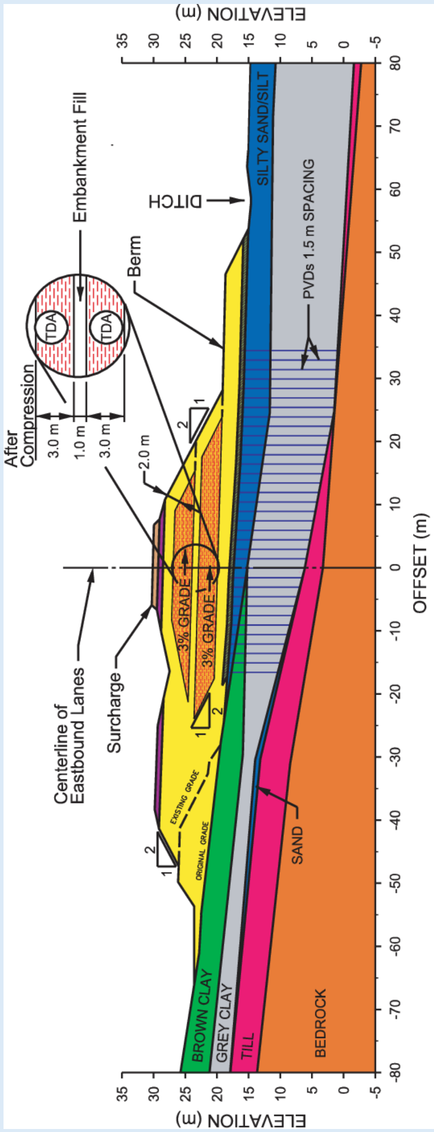


Figure 3.1: Cross section of the St. Stephen embankment, NB, Canada (after Mills et al. 2015)

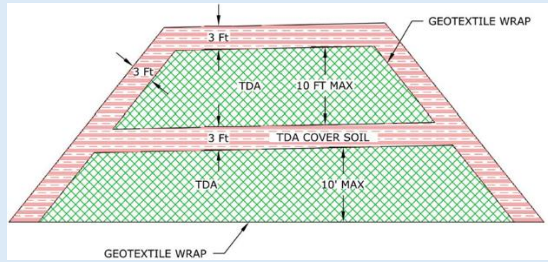


Figure 3.3: Cross section of the Dixon Landing Embankment Project, Milpitas, California (after D. Humphrey, 2003).

Figure 3.4: The Dixon Landing Embankment Project, Milpitas, California, after completion (after Humphrey 2003).

Figure 3.2: The Stephen embankment, NB, Canada after completion (after Mills et al. 2015)

3.2 Retaining Walls

3.2.1 Background

The use of tire-derived aggregate as a backfilling material behind retaining walls represents a sustainable and innovative approach to civil engineering, capitalizing on the environmental benefits of recycling scrap tires. The lightweight nature of TDA reduces the overall load on retaining structures, which can be particularly advantageous in seismic regions where reducing mass helps mitigate earthquake forces.

Many studies have demonstrated the effectiveness of TDA as a lightweight backfill material for retaining walls. Research by (D. N. Humphrey & Sandford, 1993), Cecich et al. (1996) and CalRecycle (2014a, 2014b, 2020) highlight the TDA's capacity to reduce horizontal pressures behind retaining walls, leading to favourable outcomes.

Further, Ahn & Cheng (2014) utilized shake table tests and finite element analysis, concluding that TDA-backfilled retaining walls exhibited minimal displacement, making them suitable for seismic design. The California Department of Resources Recycling and Recovery (CalRecycle) has been a strong advocate for using TDA in retaining walls. Collaborating with Caltrans and GHD Inc., they have developed standardized detail sheets for TDA backfilled retaining walls, facilitating adaptive designs for nonstandard applications. Besides its engineering advantages, TDA is often more cost-effective than sand as a backfill material. Studies by Tweedie et al., (1998a), Cecich et al. (1996) and Humphrey et al. (1993) highlight the economic benefits, noting that TDA reduces the need for carbon-intensive steel and concrete support. This reduction not only results in cost savings but also enhances environmental sustainability.

3.2.2 Design Procedures and Guidelines

Designing TDA-backfilled retaining walls follows the same procedures and theories as those for soil-backfilled retaining walls. Retaining walls are crucial for supporting the shear forces exerted by the backfill material, whether it is TDA or soil. Key factors like bearing capacity, resistance to overturning, and sliding must be taken into account when selecting a backfill material. TDA has proven to be more effective than soil in reducing the forces applied to the retaining wall, thereby mitigating the risks of overturning and sliding (Cheng, 2016).

Safety levels for TDA backfill designs can be compared to traditional soil backfill designs using the traditional factor of safety calculations, which consistently show TDA's superior performance in retaining wall design. Additionally, due to TDA's lightweight nature compared to other conventional fill materials, TDA-backfilled retaining walls require less steel and concrete for support. This not only results in cost savings by reducing the amount of steel needed but also provides environmental benefits by lowering the use of carbon-intensive concrete. Overall, TDA presents a compelling option for retaining wall design, offering enhanced safety and sustainability while adhering to traditional engineering principles.

To ensure successful application of TDA to backfill behind retaining walls, the following guidelines are recommended:

- Determine the geotechnical properties of the soil layers present at the site and that of the used TDA.
- Based on the design requirements and site conditions, select the appropriate TDA gradation and quality. The TDA used should meet the specifications of ASTM D6270 and other relevant standards.
- Calculate the volume and the number of tons of TDA required for the project using the procedure discussed in section 2.1.4 based on the wall's dimensions, the density of the TDA, and the design load.
- Ensure that the subgrade is adequately prepared to support the weight of the TDA and the retaining wall. The subgrade must be compacted and levelled to prevent both overall and differential settlement.
- Design the wall to withstand lateral earth pressures, considering active, passive, and at-rest pressures. Depending on the wall's height and the site's conditions, it can be designed either as a gravity wall or as a cantilever wall.
- Proper drainage solutions such as weep holes or drainage pipes must be employed behind the retaining wall to prevent the buildup of hydrostatic pressure.
- Used TDA layers must be enclosed with geotextile material on the top, bottom and ends. This geotextile must meet protection standards to prevent soil from migrating into the TDA volume.
- The top of the TDA layers should be covered with at least a 1 m thick layer of conventional soil.
- Routine inspections should ensure that the retaining wall is functioning as intended. Besides, proper maintenance strategies should be developed and followed.

Appropriate attention to these factors enables an effective application of TDA in retaining wall projects. This translates the efforts into a structure that is stable, long-lasting, and environmentally friendly. For instance, Figures 3.5 and 3.6 depict Wall 207, which is a typical reinforced concrete retaining wall Caltrans built in a freeway widening project in Riverside, California. In this project, the TDA played a dual role, being used both as a backfilling material and as a drainage layer.

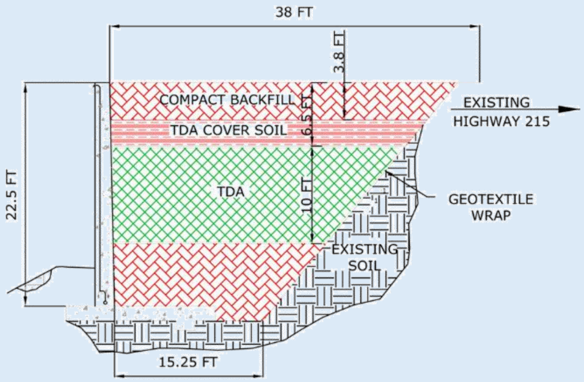


Figure 3.5: Wall 207 Cross Section (after Humphrey 2003).

Figure 3.6: Wall 207 during construction (after Humphrey 2003).

3.3 Slope stabilization

3.3.1 Background

Tire derived aggregates are increasingly being recognized as a viable solution for slope stabilization due to their unique properties, such as low density, high permeability, and good durability. Several studies have explored the effectiveness of TDA in various geotechnical applications, including the stabilization of slopes. The following section synthesizes the insights from some key research papers on this topic, providing a comprehensive overview of the use of TDA in slope stabilization.

TDA has been effectively utilized to improve the mechanical properties of expansive soils and to mitigate issues related to slope instability. (Soltani et al., 2022)investigated the combined efficacy of TDA and lime in enhancing the compressive strength and reducing the swelling potential of expansive soils. Their study found that incorporating up to 10% TDA, especially with coarse-sand-sized particles, significantly improved the soil's unconfined compressive strength (UCS) and reduced its swelling potential, making it suitable for slope stabilization applications (Soltani et al., 2022).

Arulrajah et al. (2019) focused on the use of TDA blended with waste rock for pavement base and subbase applications. They highlighted that TDA blends, especially with 2% TDA content, exhibited acceptable permanent strain behaviour and resilient modulus characteristics, making them viable for use in stabilizing road bases and potentially in slope stabilization (Arulrajah et al., 2019).

Mills et al. (2015) provided a North American overview, particularly focusing on a case study in New Brunswick, Canada, where TDA was used to reconstruct a failed highway embankment. The study underscored the importance of TDA in reducing the load on weak foundation soils, thus preventing slope failure and enhancing the stability of the embankment (Mills et al., 2015).

(Gordan et al., 2015) explored the distribution of specific gravity for laterite soil mixed with TDA and silica. They found that TDA reduced the specific gravity of the soil, which can be beneficial in reducing the weight and enhancing the stability of slopes constructed on weak or expansive soils (Gordan et al., 2015).

The research collectively suggests that TDA can significantly enhance the mechanical properties and stability of soils used in slope stabilization. The integration of TDA with other materials like lime, waste rock, and silica has been shown to further improve its efficacy, offering a sustainable and effective solution for slope stabilization challenges.

3.3.2 Design Procedures and Guidelines

The following guidelines are recommended to ensure effective application of TDA in slope stabilization projects:

- Choose the appropriate TDA gradation and quality according to the design requirements and site conditions, adhering to ASTM D6270 and other relevant standards. Use Type A TDA for light-fill applications and Type B TDA for heavier-load applications.
- Conduct geotechnical surveys to assess soil properties of the in-situ soils and the TDA used, focusing on key parameters such as density, strength, stiffness, and drainage characteristics to ensure compliance with local and federal design regulations.
- Determine the volume and the number of tons of TDA needed for the project as outlined in section 2.1.4, based on the design load and allowable settlement criteria.
- Identify potential drainage issues and ensure proper grading for drainage. In addition, design for adequate internal drainage within the TDA layer.
- Perform slope stability calculations considering TDA properties. Use limit equilibrium methods or finite element analysis.
- Assess potential settlements using compressibility data of TDA.
- Use geotextiles to separate TDA from soil and prevent clogging. Used TDA layers must be fully enclosed with geotextile on all sides.
- Cover the sides of TDA embankments with at least a 1-meter thick layer of conventional soil.
- Place TDA in layers, typically 1-2 feet thick. Compact each layer to achieve the desired density.
- In soft soil conditions, consider additional design measures such as geotextiles, geogrids, or soil stabilization techniques to enhance foundation strength and stability.
- Design the slope of the TDA layer with an adequate factor of safety, preventing sliding or erosion.
- Develop proper maintenance strategies, including erosion prevention and addressing any settling or deformation over time.

Implementing tire-derived aggregates in slope stabilization projects offers a sustainable and effective solution for enhancing soil stability and managing drainage. By adhering to these design procedures and guidelines, engineers and construction professionals can ensure the successful application of TDA, addressing both geotechnical and environmental concerns. Proper material selection, thorough site assessment, and meticulous design calculations form the foundation of a robust stabilization plan.

Coupled with stringent construction practices and ongoing monitoring, these measures help mitigate potential risks and ensure the long-term stability of the slope. Figure 3.7 shows the 2009 slope deterioration of the Interstate 94 in Bismarck, North Dakota. This slope deterioration occurred due to the inadequate shear strength of the supporting embankment soil at the site, which resulted in a four-month road closure. The engineering consultant that was retained to stabilize the slope, developed a solution that included a combination of driven piles and a lightweight TDA fill. Figure 3.8 shows the project after the repair was completed.

Figure 3.7: The 2009 slope deterioration of Interstate 94 in Bismarck, North Dakota.

Figure 3.8: Interstate 94 in Bismarck after the repair was completed.

3.4 Freeze-Thaw Prevention

3.4.1 Background

Frost heaving is one of the most common and costly challenges for municipal roads in North America. This phenomenon involves the upward swelling of soil during freezing conditions, driven by the formation and growth of ice within the soil. The process begins when freezing temperatures penetrate the ground, creating a freezing front or boundary. Ice grows upward from this point, requiring a continuous water supply delivered through capillary action in certain types of soil. The weight of the overlying soil can restrict the vertical growth of ice, often leading to the formation of lens-shaped ice layers, known as ice lenses, within the soil. Despite this restraint, the force exerted by one or more growing ice lenses can lift soil layers by as much as 300 mm or more. The impact of frost heaving is significant. Differential frost heaving can crack pavements, leading to the formation of potholes during spring, and can cause severe damage to surface structures. (Badila, 2015). Factors such as freezing rates and soil moisture content influence the severity of these effects. Addressing frost heaving is essential to minimize its costly effects on infrastructure. Strategies such as insulation, drainage, and the use of frost-resistant materials can be implemented to mitigate the impact of ice lens formation.

Tire-derived aggregates (TDA) have gained attention for their unique properties, particularly in applications requiring freeze-thaw protection. TDA is known for its excellent drainage and insulating capabilities, making it an ideal material for regions prone to cyclic freezing and thawing. When incorporated into civil engineering projects, such as roadways, TDA mitigates frost heave by serving as an insulating layer, reducing frost penetration into underlying soils and minimizing the formation of ice lenses. It also acts as a capillary break, preventing water from migrating into the overlying subbase and base layers. Additionally, TDA enhances drainage during the spring thaw, efficiently removing excess water from the roadway cross-section. These combined properties make TDA a highly effective material for managing frost-related challenges in road construction. Its flexibility and resilience also absorb stress caused by temperature fluctuations, which reduces the risk of structural damage. For instance, in colder regions, when the ground thaws in spring, subgrade soils often release excess moisture. Adding a 6 to 12-inch layer of tire shreds beneath the road can stop the subgrade soils from freezing in the first place. Moreover, tire shreds have excellent drainage properties, allowing water to flow away from beneath the roads and protecting the road surface from damage.

Since the 1990s, several researchers have investigated TDA as a cost-effective insulation material to reduce frost heave in road infrastructure. For instance, Humphrey and Eaton (1995) conducted a field trial in Maine, installing varying TDA thicknesses in gravel road sections and monitoring frost depth over two winters. The results showed that TDA significantly reduced frost penetration and frost heave compared to control sections without TDA. Acting as a thermal barrier, TDA limited heat transfer and prevented deep frost penetration into the subgrade, highlighting its potential to reduce frost damage in roads, especially in regions with harsh winters.

This innovative use of recycled materials contributes to sustainable construction practices, offering a practical solution to climate-related challenges.

3.4.2 Design Procedures and Guidelines

The following specified guidelines are recommended to ensure effective application of TDA in freeze-thaw prevention applications:

- Choose tire-derived aggregates that meet specific size requirements based on the application and ensure that the material is free from contaminants such as metal or fabric remnants.
- For a TDA layer approximately 12 inches thick, it is essential to use Type A TDA. This thickness is generally suitable for projects in the U.S. and maritime Canada. However, if the TDA layer exceeds 1 meter in thickness, Type B TDA should be used.
- Estimate the volume of TDA based on the region's anticipated freeze-thaw cycles. Consider the drainage capacity and insulation properties required for the specific project site.
- Conduct a detailed analysis of the soil, focusing on its moisture content, permeability, and frost susceptibility. TDA should be used in conjunction with soils that require enhanced insulation properties to prevent freeze-thaw damage.
- Determine the water table depth, drainage patterns, and the amount of water that might infiltrate the subgrade. TDA performs optimally in conditions where proper drainage is maintained.
- Specify the thickness of the TDA layer. In general, for freeze-thaw applications, a TDA layer of at least 150-300 mm is recommended, depending on site-specific conditions such as frost depth and anticipated loading.
- Conduct a thermal analysis to ensure the design adequately minimizes heat transfer between the subgrade and surface layers.
- Prepare the site by grading and levelling it. If needed, install a geotextile fabric between the TDA and surrounding soil to prevent the migration of fines into the aggregate, which can reduce performance over time.

- Spread the TDA evenly across the designated area. The distribution should be consistent to avoid weak points where frost can penetrate.
- Incorporate proper drainage systems, such as perforated pipes or drainage channels, to manage excess moisture. TDA provides a free-draining environment, so proper water movement away from the site is essential to prevent frost heave.

The application of TDA in freeze-thaw prevention projects offers a promising approach to enhancing the durability and performance of civil infrastructure. The material's inherent properties, such as low density, thermal insulation, and resilience, make it an effective solution for reducing the impact of freeze-thaw cycles. By incorporating TDA, infrastructure can potentially experience extended lifespans and reduced maintenance costs, providing a sustainable alternative to traditional methods. This innovative use of recycled materials not only contributes to environmental goals but also addresses critical challenges in cold climate engineering, ensuring more robust and reliable systems for future development.

Figure 3.9 shows extensive frost heave damage on the heavily trafficked Lake Drive in Robbinsdale, Minnesota. TDA was selected as the lightweight fill material for reconstructing the road. Figure 3.10 shows comparative photos taken when the original road repair project was completed and sixteen years after it was completed. It is evident from the photos that TDA has stopped frost-heave damage from occurring for nearly two decades and its protection is continuing.

Figure 3.9: Extensive frost heave damage on Lake Drive in Robbinsdale, Minnesota. (TDA Manufacturing, 2024).

Figure 3.10: Lake Drive Road repair upon original completion and sixteen years after. (TDA Manufacturing, 2024)

3.5 Foundations

3.5.1 Background

Shallow foundations are the most basic and common type of foundation used to support structures. They are often the most affordable choice because they are easy to build and do not require special equipment. They distribute structural loads over a larger area of near-surface soil, reducing the induced stresses on the foundation. Shallow foundations are suitable for various applications, including footings for buildings, retaining walls, and bridges. The most common type of shallow foundation is the isolated footing, which supports individual columns.

Soft soils are widespread in the United States, Canada and globally. Building on them poses significant safety risks due to inadequate bearing capacity, leading to failures and losses. Hence, in such sites, lightweight fills are commonly used rather than traditional heavy fills to reduce the induced loads on the subsurface, thereby increasing the factor of safety against ultimate failure. In addition, because lightweight fills reduce the induced load on the underlying soils, they also reduce the settlements.

The lightweight characteristic of TDA, coupled with its structural integrity and thermal insulation capabilities at a reasonable price, makes it a suitable material for use as an engineered backfill underneath shallow foundations.

Rashwan & Charette (2105) investigated the use of TDA as a backfill around basement walls and beneath basement slabs. The study found that TDA significantly lowered lateral earth pressures on the walls compared to traditional backfill materials. Additionally, it improved heat insulation through the walls and slabs, and its excellent drainage capacity reduced moisture retention on the walls. Likewise, Mahgoub & El Naggar (2019) investigated the use of TDA as a stress-reducing fill to protect underground pipes beneath shallow foundations. The study involved two full-scale field tests to assess the effectiveness of placing a TDA layer above metal pipes in enhancing the stress arching mechanism. Furthermore, in another study, they studied the use of TDA underneath shallow foundations utilizing three full-scale field tests and a comprehensive numerical modelling program (Mahgoub & El Naggar, 2020). The study showed that using a layer of TDA as a backfill underneath shallow foundations results in a substantial improvement in transferring the stresses and decreasing the stress influence zone underneath the footings compared to using conventional granular backfill (see Figure 3.11).

This additional innovative use of TDA contributes to sustainable construction practices, offering a practical solution allowing building on soft soils.

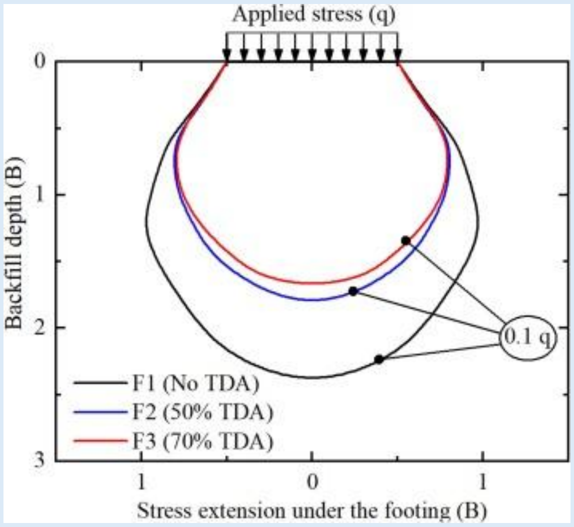


Figure 3.11: Stress influence zone underneath test footings. (Mahgoub and El Naggar, 2020)

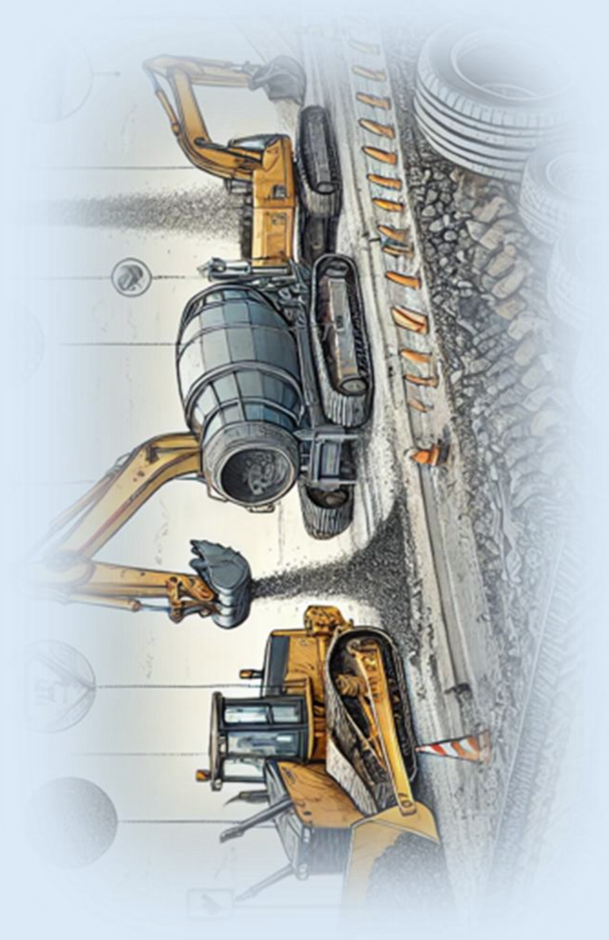
3.5.2 Design Procedures and Guidelines

The following listed guidelines are recommended to ensure effective application of TDA in structural foundation applications:

- Choose tire-derived aggregates that meet the ASTM size requirements and ensure that the material is free from contaminants such as metal or fabric remnants.
- Conduct a thorough site assessment to understand the characteristics of the existing soil, including its bearing capacity, settlement potential, and drainage characteristics. This helps to determine the compatibility of TDA with the surrounding soil.
- Determine the expected load from the structure to ensure that the TDA material can adequately support the imposed stresses. This is crucial for ensuring structural stability.
- Proper compaction of TDA is essential to achieve the desired load-bearing capacity.
- Mechanical rolling or vibratory techniques are recommended for compaction. These techniques enhance the interlocking of TDA particles, reducing voids and improving strength.
- Perform compaction in layers, typically 300 mm thick, to ensure uniformity.
- The total thickness of the TDA layer should be calculated based on the foundation load, soil conditions, and any settlement allowances.
- Where necessary, include geosynthetic materials like geotextiles to separate TDA from native soil or other fill materials. This prevents the mixing of different materials, which can negatively impact performance.
- TDA may experience creep under sustained loads. It is important to account for this long-term deformation in the design by incorporating appropriate safety factors.
- Field tests such as plate load tests and settlement monitoring are recommended to validate the

performance of TDA under site-specific conditions. Regular inspections and testing during installation are crucial to ensure that the material performs as expected.

The use of tire-derived aggregates in shallow foundation applications presents a promising and environmentally sustainable alternative to traditional materials, yet more research is required. By repurposing end-of-life tires, TDA offers a valuable solution for reducing landfill waste and conserving natural resources.



While further research and development are necessary to fully understand the long-term performance of TDA-based foundations in various soil conditions and loading scenarios, the initial studies and real-world applications have demonstrated their potential to provide cost-effective, durable, and environmentally friendly foundations.

Geoenvironmental Applications of TDA

4. Geoenvironmental Applications of TDA

4.1 Stormwater Storage, Retention, and Filtration

4.1.1 Background

Tire-derived aggregates are a cost-effective and sustainable option for stormwater management systems. Their large void space allows for significant water storage and infiltration, making them ideal for applications like storage, retention, and filtration.

Storage involves temporarily or permanently holding stormwater runoff in constructed structures or basins. This helps reduce peak flows and prevent downstream flooding. Retention focuses on collecting and storing stormwater on-site to allow for infiltration into the ground. This mimics natural hydrological processes and replenishes groundwater resources. Detention involves temporarily storing stormwater in a constructed basin and releasing it at a controlled rate to prevent flooding.

A case study in California demonstrated the effectiveness of using TDA in a stormwater retention/infiltration gallery. The project aimed to reduce the impact of urban runoff and recharge groundwater. The TDA-filled gallery provided a large surface area for water infiltration, leading to high groundwater recharge rates. In this project, a 400-foot-long infiltration gallery with a total capacity of 20,000 cubic feet of stormwater storage was constructed using recycled plastic chambers filled with TDA instead of the conventional rock-filled chambers typically used in such applications.

While TDA offers several benefits, such as reduced costs and improved infiltration rates, they may also present challenges during construction. Careful handling and compaction are essential to prevent settling and mixing with surrounding soil. The use of geotextile fabrics can help address these issues.

Overall, the case study highlights the potential of TDA as a sustainable and effective material for stormwater management. Further research is needed to evaluate their long-term performance and promote broader adoption in the industry.

4.1.2 Design Procedures and Guidelines

The following guidelines are recommended to ensure effective application of TDA in stormwater management systems applications:

- Begin by analyzing the site's existing water flow, including infiltration rates, soil composition, and seasonal water levels. Consider factors such as the volume and rate of stormwater runoff.
- Determine whether the system is designed for storage, retention, or filtration. Each application has different design requirements in terms of capacity, material sizing, and layout.
- Ensure the project meets regulatory requirements, including environmental standards and local water management guidelines. Obtain necessary permits.
- Select appropriate TDA sizes based on the intended application. Larger pieces (i.e., Type B) provide better drainage and void space, making them ideal for stormwater storage. Smaller pieces (Type A) may be more suited for filtration or retention systems where finer material aids in filtering contaminants.
- Ensure that the TDA material is free from contaminants such as heavy metals or oils. It should meet or exceed standards set by authorities governing recycled materials.

Design Specifications for Stormwater Storage Systems

- Calculate the volume of stormwater expected from a design storm event. This will help determine the overall capacity needed for the system.
- For maximum efficiency, layer TDA within storage basins. A typical setup might include a TDA base with finer aggregates or geotextiles layered above for filtering finer particles.
- Utilize the high porosity of TDA to maximize water storage capacity. Calculate the void ratio of the chosen TDA size and the expected overburden pressure to determine the amount of water that can be stored within the material itself.

Design Specifications for Stormwater Retention Systems

- Create retention basins or trenches using TDA as a key component. TDA can enhance water retention, due to its porous properties, allowing water to percolate and slowly release over time.
- Adjust the depth and layout of TDA layers based on soil infiltration capacity. Integrating TDA with native soils or other aggregates can improve long-term retention.
- Ensure stability of the TDA layer, especially in larger retention basins, by

incorporating anchoring systems or using a gravel overlay to prevent material movement during high-flow events.

Design Specifications for Filtration Systems

- Identify the contaminants present in the stormwater and design the filtration system to target specific pollutants. TDA is effective in removing certain contaminants, such as heavy metals and hydrocarbons.
- Consider using TDA as one layer in a multistage filtration system, combining it with materials such as sand, gravel, or activated carbon. This enhances filtration efficiency by targeting different contaminants at different stages.
- Design the system to allow easy access for maintenance, such as removing or replacing TDA over time as it captures pollutants.

- In larger storage and retention systems, include perforated pipes to allow for controlled drainage and distribution of stormwater. The pipes should be designed to ensure proper flow through the TDA layers.
- Design overflow structures to manage excess water during extreme storm events. Ensure these structures are capable of handling the design flow without causing erosion or structural damage to the TDA layers.
- Properly compact the TDA during installation to ensure structural stability and avoid excessive settling. However, do not over-compact, as this could reduce the material's porosity and effectiveness.
- Install TDA in layers of specified thickness, usually between 300mm to 600mm, depending on the application.
- Barriers or edging materials should be utilized to prevent migration of the TDA outside the intended application area, especially in open systems such as retention ponds.
- Inspect the system periodically for signs of clogging, erosion, or settlement. Infiltration systems monitor for reduced flow rates, which may indicate that the TDA is saturated with contaminants and needs replacement.
- Plan for periodic replacement of TDA in filtration systems based on the material's lifespan and contaminant load. Typically, the interval for replacement depends on the site-specific pollutant levels.
- Ensure that sediment entering the system is managed with upstream

barriers or sediment traps to prevent clogging of the TDA.

- Evaluate the risk of leachate from TDA, particularly if the material will come into direct contact with groundwater. Incorporate a geotextile layer or liner to contain potential leachates if necessary.

By following these procedures, TDA can be effectively incorporated into stormwater storage, retention, and filtration systems, providing an environmentally friendly and durable solution for managing runoff.

As an example, Figure 4.1 shows the TDA stormwater management system for the Beacon Bluff redevelopment project in St. Paul, Minnesota. TDA was used to filter contaminated stormwater runoff, previously directly discharged untreated into the Mississippi River. A specialized metal grate is incorporated into the system design to trap contaminants, with around 90% of the trapped contaminated sediments captured in a sump.

Figure 4.1: The TDA stormwater management system for the Beacon Bluff redevelopment project (First State Tire Recycling, 2020).

Likewise, Figures 4.2 and 4.3 show the TDA infiltration system at The Paynesville Secondary School in West-Central Minnesota during construction and after completion, respectively. An underground stormwater infiltration gallery was designed to be utilized beneath a sidewalk passing through the school's two parking lots. This eliminated the need for open stormwater ponds, a year-round safety hazard.

Figure 4.2: The TDA infiltration system at The Paynesville Secondary School during construction. (Park et al., 2023)

Figure 4.3: The TDA infiltration system at The Paynesville Secondary School after completion (Park et al., 2023).

4.2 Landfill Leachate and Gas Collection Systems

4.2.1 Background

Tire-derived aggregates are a sustainable and cost-effective alternative to traditional materials in landfill gas and leachate collection systems. Due to their high permeability, lightweight nature, and durability, TDA is ideal for drainage applications within modern municipal solid waste (MSW) landfills (Cheng, 2016).

TDA can be used as a gravel substitute in various landfill components, including gas collection trenches, header pipe protection, and leachate recirculation systems. Studies have shown that TDA can effectively handle the challenging conditions found in landfills, such as high leachate loads and potential clogging.

One of the primary concerns with using TDA in landfill applications is the potential for clogging. Research efforts by (Reddy et al., 2008) and several other researchers have investigated this issue, exploring factors like leachate characteristics, landfill type, and TDA properties. While some clogging can occur, TDA has demonstrated consistent performance in drainage applications, even when partially clogged. In addition to their drainage capabilities, TDA can also contribute to reducing volatile organic compound (VOC) emissions from landfills. Studies have shown that TDA can effectively retard the movement of VOCs through clay liners, minimizing their potential migration into the surrounding environment (Edil et al., 2004).

4.2.2 Design Procedures and Guidelines

The following listed guidelines are recommended to ensure the effective application of TDA in landfill leachate and gas collection systems:

- Type B TDA (50–300 mm in size) is typically recommended for landfill applications. This larger size allows for better drainage and gas collection while maintaining structural integrity.
- Ensure the TDA is free of hazardous materials and contaminants, such as metals or chemicals, that could compromise landfill integrity or affect groundwater quality.
- The typical bulk density of TDA is 500–650 kg/m^3, which should be factored into design calculations to ensure proper load distribution within the landfill system.
- Assess the soil type and conditions of the landfill site. TDA works best in locations with stable subgrade conditions. Soft or compressible soils may require reinforcement before TDA installation.
- Conduct a thorough evaluation of the landfill's proximity to groundwater sources, considering potential interactions between leachate and surrounding areas.

- ***Leachate Collection Design***
  - The TDA layer used for leachate collection should typically be 0.3 to 1.0 meters thick, depending on the landfill design and anticipated leachate volume.
  - TDA should have a permeability of 0.01 to 1.0 cm/s, depending on the required flow rate of the leachate collection system. This ensures efficient leachate movement while avoiding ponding or accumulation.
  - Install a protective layer of geotextile above and below the TDA to prevent the migration of fines, which can clog the drainage system.
  - Place perforated pipes within or on top of the TDA layer for enhanced leachate collection. These pipes should be spaced based on the landfill's leachate generation rates and hydrological modelling.

- ***Gas Collection Design***
  - TDA's high gas permeability (up to 1000 $cm^3/cm^2/sec$) makes it an excellent medium for landfill gas extraction systems.
  - Install a 0.6 to 1.0-meter-thick TDA layer above the waste mass to collect gas, placing perforated pipes within the TDA layer to capture the generated gases.
  - Space gas extraction wells appropriately to ensure optimal gas capture efficiency. Typical well spacing ranges from 15 to 30 meters, depending on the specific landfill gas generation rates and the depth of the TDA layer.
- TDA experiences more initial settlement compared to conventional materials, such as gravel or sand. When calculating final design elevations, allow for extra vertical settlement in the TDA layer (approximately 10% for moderate loads).
- Light compaction of the TDA layer is recommended to minimize future settlement while maintaining high permeability. Excessive compaction may reduce the material's effectiveness.
- TDA has low thermal conductivity, which can help retain heat in the landfill. This can promote faster waste decomposition and enhanced gas generation in colder climates.
- TDA should be placed in thin layers (0.3 to 0.6 meters) and lightly compacted to avoid excessive deformation. Use equipment with wide tracks to distribute loads evenly and minimize rutting.
- Ensure that the TDA is separated from finer materials using

geotextiles to prevent clogging and maintain drainage efficiency.

- After installation, conduct permeability and compression tests, if possible, to ensure the TDA meets design criteria.
- Monitor the performance of the leachate and gas collection systems regularly to detect any blockages, settlements, or gas flow restrictions.
- Check for the potential clogging of pipes and geotextiles. Replace or clean them as necessary to maintain system efficiency.
- Track settlement over time and adjust the gas well heights or leachate drainage pipes if significant settlement occurs to prevent system inefficiencies.

Overall, TDA offer a sustainable and efficient solution for landfill gas and leachate collection systems. Their high permeability, lightweight nature, and ability to reduce VOC emissions make them a valuable asset in modern landfill design and management.

Figure 4.4: Installation of gas collection pipe and spreading TDA in the gas collection trench (Patenaude and Wright, 2011).

4.3 Septic Systems

4.3.1 Background

Septic systems are underground wastewater treatment structures commonly used in areas without access to centralized sewer networks. These systems typically consist of a septic tank separating solids from liquids and a drain field, where the effluent is dispersed and further purified as it filters through soil layers. Traditionally, crushed rock or gravel serves as bedding material in the drain field to promote drainage and support the distribution pipes. However, tire-derived aggregates have gained recognition as a cost-effective and eco-friendly alternative to conventional aggregates. TDA offers several advantages for drainage applications. It provides higher permeability than traditional gravel and has a significantly lower unit weight. Additionally, TDA's larger surface area per unit volume creates more space for biofilm development, enhancing the biological treatment of wastewater as it passes through the system. Unlike rock aggregate production, which involves resource extraction, TDA repurposes waste tires, preventing them from ending up in landfills and mitigating environmental harm.

Given these benefits, TDA often outperforms traditional aggregates and can be more economical. In fact, it has been successfully used in drain fields across the U.S. for over two decades, including in states such as Arkansas, California, Colorado, Georgia, Iowa, Kansas, New Mexico, New York, North Carolina, South Carolina, Texas, Vermont, and Virginia (Daniels & Bird, 1993; Envirologic, 1990; Finney et al., 2013; Geosyntec Consultants, 2008; Grimes et al., 2003; McKenzie, 2003; Zicari, 2009). The primary driver for adopting TDA has been economic savings. Depending on factors like production and transportation costs, drain field construction using TDA can reduce expenses by 10% to 90% compared to rock aggregate (McKenzie, 2003). Since TDA has only one-third the density of gravel, a significantly smaller amount is needed—for example, around 15 tons of TDA compared to 50 tons of conventional gravel for a typical single-family home. Furthermore, studies have consistently shown that TDA promotes robust microbiological and macrobiological activity in leach fields. These studies confirm that TDA supports a thriving population of bacteria and organisms, facilitating effective biofilm treatment of the organic components in leachate, even in systems ranging from three months to eight years of age (Grimes et al., 2003; Amoozegar & Robarge, 1999; Finney et al., 2013).

As part of a demonstration project, two septic systems utilizing TDA were installed in Weld County, Colorado (Doak, 2000, 2001). Each system was designed to serve a single-family residence and comprised a septic tank, a distribution box, and a divided leach field. The leach fields for both systems featured trenches filled with either TDA or traditional rock aggregate, with each trench section equipped with two sampling ports to monitor effluent.

One system began operation in April 1998, while the second was activated in the early spring of 2000.

After the first system became operational, effluent samples were collected quarterly. The liquid was consistently found in both TDA trench sampling ports, whereas in the rock aggregate trench, the liquid was absent from the port furthest from the distribution box. This discrepancy may be due to the rock aggregate's greater capacity to retain liquid or the potential settling of the distribution line, which could have restricted liquid flow toward the end of the trench. Testing of the effluent revealed the presence of various elements, including barium, lithium, copper, iron, manganese, vanadium, and zinc. The rock trench samples exhibited higher concentrations of these elements compared to the TDA trench samples. However, total suspended solids (TSS) concentrations were significantly higher—ranging from 10 to 50 times—in the TDA trench effluent than in the rock trench effluent. Despite these differences, the concentrations of inorganic compounds remained below the groundwater protection standard, except that the concentration of perchloroethylene (PCE) slightly exceeded the standard. Further investigation determined that the source of the PCE contamination was the TDA material itself, not the septic system. In addition to PCE, trace amounts of trichloroethene (TCE), 4-methyl-2-pentanone, and cis-1,2-dichloroethene (cis-1,2-DCE) were detected. However, this can be attributed to contamination in the TDA material. Over time, PCE concentrations declined, but samples collected six months after the operation began revealed medium to high levels of cis-1,2-DCE for the first time. This shift was attributed to the anaerobic degradation of TCE to cis-1,2-DCE.

Results from the experiment indicated that TDA outperformed rock aggregate, demonstrating its potential as a viable alternative for use in leach field applications. Following the success of this demonstration project, TDA was officially approved for use in septic drainage fields throughout Colorado.

Likewise, a full-scale septic system was constructed in Siglunes, Manitoba, to evaluate the performance of Type A TDA compared to natural aggregate in a septic field and to assess its potential metal-leaching effects (Badila, 2021). The septic system featured a two-zone, trench-style field that received wastewater from a two-compartment septic tank serving a three-bedroom house. Figure 4.5 shows the general layout of the system.

Figure 4.5: General layout of the system (after Badila, 2021)).

The trench system had a total length of around 195 m and consisted of eight trenches, each measuring 24.40 m long, 600 mm wide, and 600 mm deep below ground level. Half of the trenches were filled with 500 mm of natural aggregate, and the other half was filled with TDA, as shown in Figure 4.6. A non-woven geotextile filter fabric was placed between the TDA and natural aggregate layers, then the trenches were then filled with 460 mm of sandy loam soil. Effluent quality was monitored within the trenches and in the soil beneath (vadose zone) at depths of 300 mm and 900 mm. Figure 4.7 shows the trench installation stages. It is worth mentioning that 16.71 tonnes of TDA were used in the tranches compared to 60 tonnes of natural aggregate.

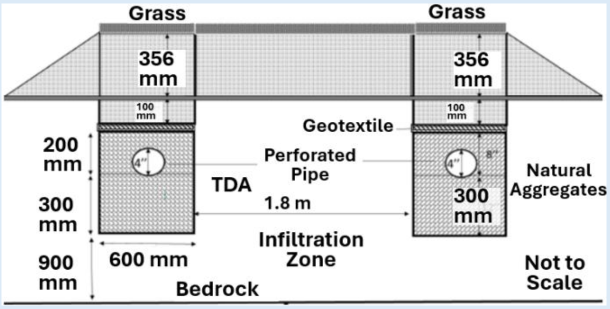


Figure 4.6: Trench system details (after Badila, 2021)

Comparative testing between TDA and natural aggregate revealed that both systems effectively reduced COD, phosphorus, and ammonia concentrations, with no significant differences between the two materials. Metal concentrations in the vadose zone, including silver (Ag), aluminum (Al), copper (Cu), iron (Fe), and zinc (Zn), remained below the limits set by the National Secondary Drinking Water Regulations (NSDWRs). However, manganese (Mn) exceeded NSDWR thresholds at a depth of 1 foot in both systems. Additionally, Zn, Mn, Cu, Fe, and chromium (Cr) levels in soil samples were within or below the typical ranges found in uncontaminated soils, both in Manitoba and globally. These results confirmed that TDA is a viable and environmentally safe substitute for natural aggregate in septic fields.

Figure 4.7: Trench installation stages

4.3.2 Design Procedures and Guidelines

When designing septic systems using TDA, the primary focus is on enhancing the drainage properties and storage capacity within the system's drain field. Here are the key design considerations and guidelines for using TDA in septic systems:

- The first step in the design involves performing a site assessment in which:

- Conduct a soil percolation test to ensure the site can adequately absorb treated effluent.
- Identify the groundwater table to determine separation distances between the septic bed and water sources.
- Analyze site topography to ensure proper gravity flow or pump configuration.

- To ensure proper drainage and aeration, use clean TDA particles free from contaminants such as metals, oils, or hazardous materials, with a typical size of 25–50 mm. Fine particles or dust should be minimized to prevent clogging.
- The Thickness of the TDA Layer used as a drainage layer within the system is often between 300 mm and 450 mm, but this depends on local regulations and percolation needs.
- Use TDA to replace gravel in leach trenches to facilitate percolation and airflow. Typical trench width is 450 to 900 mm, whereas the recommended TDA trench depth is 250 mm to 600 mm.
- Distribute TDA evenly within the trench to ensure consistent drainage and aeration.
- Ensure at least 150 mm of TDA below the perforated pipe to maintain drainage efficiency.
- Install perforated pipes within the TDA layer, ensuring the pipes are level to promote uniform effluent distribution.
- Cover the TDA layer with a non-woven geotextile fabric before backfilling with soil. This prevents soil migration while maintaining the system's permeability.
- Maintain at least 300mm to 600 mm of unsaturated soil between the TDA layer and the groundwater table.
- Cover the geotextile layer with native soil or approved material, ensuring no sharp materials puncture the fabric.
- Light compaction is recommended to stabilize the soil layer without compressing the TDA. Avoid heavy equipment directly on the TDA layer.
- Follow local code for horizontal distances to wells, water bodies, and property lines.

The design process for a leach field using TDA is largely similar to that of a traditional system employing materials like rock or gravel. The main difference lies in adapting the design to account for TDA's unique engineering properties. Typically, these projects use type A TDA, which offers a suitable range of particle sizes that are large enough to ensure excellent hydraulic conductivity.

Applications of TDA in Rubberized Concrete


5. Applications of TDA in Rubberized Concrete

5.1.1 Background

The use of TDA in concrete mixes is gaining much attention due to its potential to improve freeze-thaw durability and offer an environment-friendly alternative for recycling End-of-life tires. Freeze-thaw cycles are a critical concern in cold climates, leading to the deterioration of concrete structures. The resilient nature of rubber particles from recycled tires can improve the material properties of concrete and mortar, enhancing their resistance to freeze-thaw damage. This section discusses the latest research in the area of using TDA in freeze-thaw damage prevention applications, highlighting experimental findings, methodologies, and their implications for sustainable construction practices.

(Han et al., (2023) conducted an extensive study on rubberized concrete, examining the effects of adding scrap tire rubber particles of varying sizes and contents on the compressive strength during freeze-thaw cycles. They found that rubber particles significantly restricted the decrease in concrete strength and weight loss during these cycles. The study proposed a forecast model for rubberized concrete compressive strength, considering particle size, content, and pretreatment methods, which showed strong agreement with several other available experimental results. Likewise, Guelmine (2022) investigated the freeze-thaw durability of concrete containing rubber aggregate from tire waste (RATW). Various mixes with RATW ratios of 5%, 10%, and 15% were tested. The results indicated that rubber concrete had higher resistance to freeze-thaw cycles compared to plain concrete. The study emphasized the innovative use of RATW to extend the life of concrete structures in cold climates while reducing landfill waste.

Maddalena (2023) focused on the freeze-thaw resistance of mortar with recycled end-of-life tires at varying particle sizes. The study showed that smaller tire particles significantly improved freeze-thaw resistance and reduced water absorption by up to 52%. This indicated that fine rubber particles could enhance the durability of cementitious mortars, providing a sustainable alternative for construction materials (Maddalena, 2023).

Chen et al. (2022) explored the performance of sand-based autoclaved aerated concrete (SAAC) composites mixed with End of life tire particles. They found that optimal compressive and flexural strengths were achieved with 2.0 wt.% of 750-μm-sized waste tire particles, along with low mass-loss rates and improved impermeability performance. This study demonstrated the potential for SAAC composites to withstand freeze-thaw cycles effectively.

Alsaif et al. (2019) evaluated the freeze-thaw performance of steel fibre-reinforced rubberized concrete (SFRRuC), particularly for flexible concrete pavements. The study highlighted that SFRRuC could endure 56 freeze-thaw cycles with minimal scaling and no internal damage, making it a viable alternative for long-lasting flexible pavements.

5.1.2 Design Procedures and Guidelines

The following listed guidelines are recommended to ensure the effective application of TDA in rubberized concrete:

- Choose appropriate TDA based on particle size, shape, and composition. TDA is typically categorized by particle size: fine, medium, or coarse, with each size impacting the workability and mechanical properties of the concrete differently.
- Select an appropriate type of cement (e.g., Portland cement) that aligns with the specific mechanical requirements of the project.
- Ensure the proper gradation of fine aggregates, typically sand, is consistent with the desired mix design.
- Utilize clean water, free of contaminants, to achieve consistent hydration during mixing.
- Conduct preliminary tests to determine the optimal ratio of TDA to conventional aggregates. Generally, a TDA replacement of 5-15% by volume is recommended for structural applications. Higher percentages of TDA will reduce compressive strength but increase elasticity.
- The incorporation of TDA typically requires adjustments in the water-cement ratio to maintain workability, as rubber tends to absorb less water compared to conventional aggregates. An initial range of 0.45-0.55 is suggested.
- Use plasticizers or superplasticizers to improve the workability of the concrete without adding excessive water. If necessary, consider adding air-entraining agents to improve freeze-thaw resistance.
- Ensure adequate mixing time to achieve uniform distribution of TDA within the concrete. Over-mixing may lead to degradation of rubber particles.
- Control the addition of TDA during batching to prevent clustering of rubber particles. Introducing the TDA gradually during the mix process helps ensure an even distribution.
- Regularly check the consistency of the mix to ensure proper workability and homogeneity. Slump tests are recommended to

evaluate the consistency of fresh concrete.

- Ensure the formwork is properly designed and braced to support the potentially reduced density of the rubberized concrete.
- Apply vibration cautiously to avoid segregation. The rubber content can affect the compaction process, so appropriate vibration tools and techniques must be employed.
- Be aware that TDA may influence the surface texture. Extra attention should be paid to surface finishing techniques to achieve the desired texture and smoothness.
- Extend the curing time as necessary due to the slower hydration rate associated with rubberized concrete. A curing period of 7 to 28 days is typically recommended, depending on the ambient conditions.
- Keep the surface moist during the curing process, especially in hot and dry climates, to prevent surface cracking or improper curing.
- Be prepared for a reduction in compressive strength proportional to the amount of TDA in the mix. The reduction could be up to 50% with higher TDA content.
- Rubberized concrete shows increased ductility and energy absorption capacity, which is beneficial for applications requiring enhanced resilience, such as in seismic regions.
- Rubberized concrete exhibits lower shrinkage but higher creep compared to conventional concrete. These characteristics must be factored into structural designs.
- Rubberized concrete tends to have better freeze-thaw resistance due to the flexibility of the rubber particles. However, ensure air-entrainment to further enhance this property, especially in cold climates.
- Tire-derived aggregates may improve resistance to certain chemicals, such as acids, but regular testing should be performed to assess durability in aggressive environments.
- Conduct laboratory tests such as compressive strength, modulus of elasticity, and splitting tensile strength to validate the performance of the rubberized concrete mix.
- Implement on-site quality control procedures, including slump tests and core sampling, to ensure the mix performs as expected in real-world conditions.

By following these guidelines and performing the necessary testing, rubberized concrete with TDA can be effectively used in various civil engineering applications while contributing to sustainability and waste reduction.

Applications of TDA in Vibration Dampening

6. Applications of TDA in Vibration Dampening

6.1.1 Background

Tire-derived aggregates are increasingly recognized for their potential to control vibrations in various civil engineering applications. Whether caused by traffic, machinery, or seismic activities, vibration can lead to structural fatigue, noise pollution, and discomfort. TDA's unique properties, such as high elasticity, low density, and superior damping characteristics, make it an ideal material for reducing these vibrations. Its ability to efficiently absorb and dissipate energy allows it to outperform traditional materials like gravel or sand to mitigate ground-borne vibrations. The porous structure of TDA not only enhances its vibration-damping abilities but also makes it lighter and easier to transport and install. As the demand for sustainable infrastructure grows, TDA is emerging as a cost-effective and environmentally responsible solution for vibration control in construction, railways, and roadways.

For instance, while offering convenient urban transportation, the increasing popularity of light rail transit can also lead to significant ground-borne vibrations that may disrupt nearby communities. Traditional methods to mitigate these vibrations, such as elastic track fasteners and vibration isolation systems, can be expensive, prompting a search for more affordable and effective alternatives. Recent research suggests that tire derived aggregate could be a viable solution. TDA has demonstrated its ability to dampen vibrations in railway infrastructure. Studies have shown that incorporating TDA into the sub-ballast layer or in the ties of light rail tracks can significantly reduce ground-borne vibrations (e.g., Wolfe et al., 2004; Cheng, 2016; Zhang et al., 2022; Farooq et al., 2022). This is achieved by absorbing and dissipating the energy of the vibrations, thereby minimizing their impact on surrounding areas.

Another application of TDA in vibration control is in railway embankments. Rail systems generate significant vibrations, which can propagate through the ground and affect nearby structures. Research has shown that embedding TDA in railway embankments can significantly reduce the transmission of these vibrations. In such applications, TDA are often used in combination with traditional soil or gravel fills to create a composite system that offers both structural stability and vibration damping. For example, a study conducted by Li et al. (2024) evaluated the use of TDA in railway embankments and found that it reduced ground-borne vibrations by up to 50%. This makes TDA an effective solution for mitigating vibrations in areas where traditional vibration control methods may be less effective or more costly.

Furthermore, TDA's robust vibration absorption properties make it a promising material for seismic isolation (Moussa and El Naggar, 20221, 2022, 2024). In the event of an earthquake, TDA can act as a protective cushion, reducing the transmission of seismic energy to the railway infrastructure. Given its effectiveness, affordability, and environmental benefits, TDA presents a compelling alternative to traditional vibration mitigation methods for light rail systems.

Figure 6.1: Spreading TDA during vibration damping installation for light rail (Cheng, 2016).

6.1.2 Design Procedures and Guidelines

The following listed guidelines are recommended to ensure the effective application of TDA in vibration control applications:

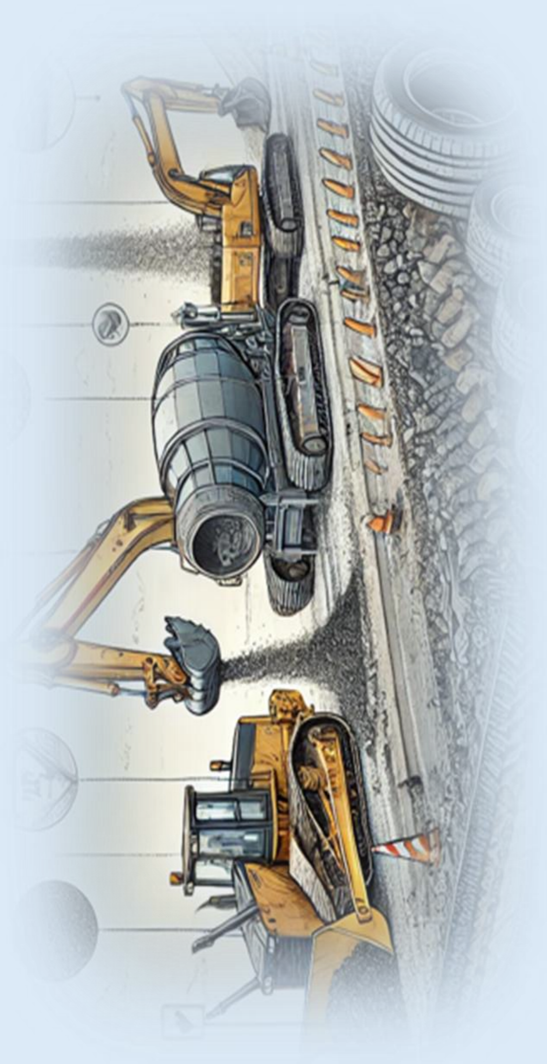
- TDA size impacts how the material behaves under dynamic loads. Choose a suitable size for the intended application.
- The density of TDA ranges from 500 to 800 kg/m^3, as mentioned earlier. Lower density materials are more effective in absorbing vibration energy.
- TDA exhibits high damping capabilities due to its elasticity and low stiffness. Laboratory testing should be conducted to assess the damping ratio for specific applications.
- Identify the frequency, amplitude, and duration of vibrations to be controlled.
- Understand the load distribution and pressures exerted on TDA layers under operating conditions.
- Assess the soil profile, groundwater conditions, and temperature variations, which may affect the performance of TDA.
- The thickness and configuration of TDA layers play a significant role in vibration attenuation. Key factors include:

  - A minimum thickness of 300 mm is recommended for most applications. For high-frequency vibration environments, thicker layers may be necessary for optimal damping.

- TDA must be compacted in layers (150-300 mm) to ensure uniformity and performance.
- In cases where fine particles are present, a geotextile fabric should be placed between TDA and adjacent materials to prevent contamination and ensure long-term effectiveness.

- Proper installation is crucial to ensure the effectiveness of TDA in vibration control. Follow these steps for best performance:
- The base must be levelled and free of debris. If required, apply a levelling layer of compacted soil or gravel.
- Place the TDA in 150-300 mm lifts and compact each layer to achieve the required density. Check for uniform thickness and compaction across the installation area.
- Use edge restraints or geotextiles to prevent lateral spreading of TDA during operation.
- Conduct post-installation tests, such as plate load tests or vibration measurements, to verify that the installed TDA meets performance criteria.

The use of TDA in vibration control applications offers an effective solution due to its damping properties and resilience. By following the design procedures outlined above, engineers can ensure that the installation performs as expected while maintaining structural integrity and environmental safety.



Economics of Tire-Derived Aggregate

7. Economics of Tire-Derived Aggregate

7.1.1 Economics of TDA

The utilization of Tire-Derived Aggregate has emerged as a viable and sustainable alternative to traditional construction materials. Derived from shredded scrap tires, TDA offers a combination of performance benefits, economic benefits, and environmental advantages.

TDA's versatility extends to various applications in civil engineering, geotechnical engineering, and environmental remediation. It can be used as a lightweight fill for embankments, retaining walls, and bridge approaches, improving stability and reducing construction costs. In geoenvironmental engineering, TDA serves as an effective drainage layer in landfill caps and liners, preventing leachate migration and protecting groundwater resources. Additionally, TDA's ability to absorb and degrade contaminants makes it a valuable tool for environmental remediation projects, such as landfill capping and contaminated soil cleanup.

The economic advantages of TDA are substantial. Due to its lower acquisition and transportation costs, TDA is often more cost-effective than traditional materials like gravel, sand, and crushed stone. Studies have demonstrated that using TDA as a lightweight fill can reduce construction costs by up to 50%, making it an attractive option for projects with tight budgets (El Naggar et al., 2020;Loo et al., 2024). Furthermore, TDA's availability as a waste product can significantly reduce material acquisition costs, further enhancing its economic appeal.

Beyond economic benefits, TDA offers significant environmental advantages. Diverting scrap tires from landfills helps reduce waste disposal impacts and conserve natural resources. Studies have consistently shown that TDA's environmental footprint is lower than that of traditional materials, including lower carbon emissions when used as lightweight fill. By utilizing TDA, construction projects can contribute to a more sustainable future and reduce their overall environmental impact.

While TDA presents several advantages, it is important to address potential challenges. Variations in shredding processes and the lightweight nature of the material may cause quality and handling difficulties. However, properly planned and implemented, these challenges can be effectively mitigated.

Based on the above, tire-derived aggregate offers a promising solution for the construction industry, combining economic benefits with environmental sustainability. Its versatility, cost-effectiveness, and positive environmental impact make it a valuable alternative to traditional construction materials. As the construction industry continues to seek more sustainable and efficient solutions, TDA is poised to play a significant role in shaping the future of infrastructure development.

7.1.2 Life-Cycle Cost Analysis of Tire-Derived Aggregate

Life-cycle cost analysis (LCCA) is a critical approach to evaluate the total costs associated with a product or material throughout its lifespan. For tire-derived aggregate, this methodology assesses not only the direct construction expenses but also the environmental and long-term economic benefits. Compared to traditional aggregates, such as gravel or crushed stone, TDA offers potential advantages in both cost savings and environmental impact reduction, as shown by several studies. This analysis explores the use of TDA in various civil engineering and geotechnical applications, comparing it with natural aggregates through the lens of LCCA.

7.1.3 TDA Life-Cycle Cost Components

Figure 4.1 illustrates the main components of a typical TDA life-cycle cost analysis, covering everything from raw material acquisition to end-of-life expenses. This approach is adopted from the Federal Highway Administration's LCCA method.

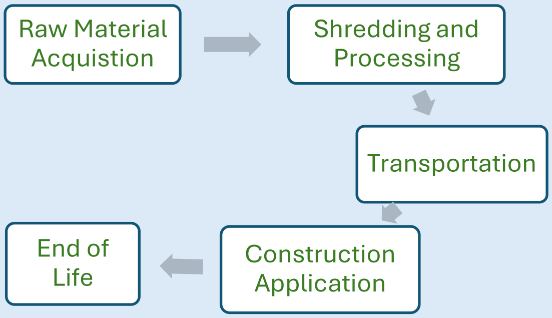


Figure 7.1: Main components of a typical TDA life-cycle cost analysis.

Raw Material Acquisition

The journey of TDA begins with the collection of scrap tires. These tires, which would otherwise end up in landfills, are repurposed into a valuable material. This process not only reduces landfill waste but also turns waste into utility. Costs incurred at this stage include tire collection, transportation to recycling centers, and preliminary processing.

Shredding and Processing

Next, the scrap tires undergo shredding and additional processing to become TDA. This stage requires significant resources, such as shredding equipment, energy, labour, end product quality control and maintenance—each contributing to the overall costs of production.

Transportation to the Site

The processed TDA is then transported to construction sites. Since scrap tires can be often available in urban areas, the transportation distance—and hence cost—is usually less than that for natural aggregates from distant quarries.

Additionally, the lightweight nature of TDA results in lower fuel consumption and reduced emissions during transport.

Construction Application

Once delivered, TDA is utilized in geotechnical construction as lightweight fill, drainage material, or for vibration mitigation. Installation and maintenance are often more economical compared to conventional materials due to TDA's light weight, which simplifies excavation and compaction efforts.

End of Life

At the end of its service life, TDA has two possible paths: disposal or reuse. Its durability allows for recycling in secondary applications, providing additional cost savings over landfill disposal.

7.1.4 Economic and Environmental Benefits of TDA

The LCCA of TDA highlights several economic and environmental benefits:

Cost Savings

Multiple studies show that TDA offers significant cost savings over traditional aggregates. For example, embankment projects using TDA instead of soil or lightweight alternatives such as expanded polystyrene (EPS) reduced project costs by as much as 60%. TDA's affordability extends across applications, including stormwater management and pavement subgrades, where it often costs 30–40% less than traditional materials (Arulrajah et al., 2019; Abo Abdo and El Naggar, 2023).

Reduced Environmental Impact

Studies confirm that TDA has a lower environmental footprint than natural aggregates. TDA production consumes less energy, resulting in fewer greenhouse gas (GHG) emissions. Brown and Roseen (2013) found that TDA emits 1.66 kg of CO_2 equivalent per cubic meter during production, compared to 3.52 kg for gravel. TDA also produces fewer emissions during transport and installation, contributing to further environmental benefits.

Longevity and Low Maintenance

TDA-backfilled structures, such as retaining walls and road subgrades, exhibit lower maintenance requirements due to TDA's durability and stability. In a 10-year comparison, TDA retaining walls required 88% less maintenance than EPS alternatives. Likewise, Jones and Ahmed (2018) demonstrated that TDA offers lower installation and transportation costs compared to crushed stone. Over a 20-year period, pavement subgrades with TDA resulted in 10.5% total cost savings due to reduced maintenance needs.

Versatility and Secondary Applications

TDA's ability to serve in various roles—including drainage layers, vibration mitigation, and lightweight fill—adds to its appeal. Additionally, it can generate revenue through sales to industries like asphalt paving and tire recycling, further enhancing its economic sustainability.

7.5 Section Summary

The LCCA of TDA highlights both the economic and environmental advantages it offers in geotechnical applications. From an economic perspective, TDA is often more cost effective than traditional materials, especially when factoring in its lightweight properties, drainage capabilities, and potential to reduce construction costs, such as lessening the load on foundations and minimizing settlement issues. Additionally, using TDA helps lower transportation and material costs since it reuses End of life tires, which would otherwise end up in landfills.

Environmentally, incorporating TDA supports sustainable infrastructure development by promoting the circular economy and reducing environmental burdens. Recycling tires into aggregate mitigates waste generation and decreases the need for virgin materials, which helps conserve natural resources. Moreover, TDA offers technical benefits such as excellent insulation properties and effective drainage, making it suitable for roadbeds, retaining walls, embankments, and landfill covers.

However, the sustainable use of TDA requires careful design and construction practices. For example, TDA's compressibility needs to be addressed through proper engineering design to ensure long-term stability. Additionally, understanding its behaviour in various environmental conditions—such as in the presence of moisture or chemical exposure—is critical for ensuring the material performs reliably throughout the project lifecycle.

Proper design, material testing, and monitoring are key to fully realizing the benefits of TDA in geotechnical applications. TDA transforms waste into value in a way that aligns with both economic and environmental goals.

Notable Projects that Utilized TDA

8. Notable Projects that Utilized TDA

TDA has been utilized worldwide in various civil engineering applications, such as lightweight fill for retaining walls and embankments, filter media in wastewater treatment, and vibration damping for railways and seismic events. Below is a snapshot of notable TDA projects in the US and Canada, along with detailed descriptions and project portfolios for each.

8.1 United States of America

8.1.1 Caltrans Retaining Wall Pilot Projects, California

The California Integrated Waste Management Board (CIWMB), now known as the Department of Resources Recycling and Recovery (CalRecycle), collaborated with the California Department of Transportation (Caltrans) to implement two pilot projects focused on retaining walls. These projects, the Wall 119 and Wall 207 Projects, aimed to explore alternative backfill materials in retaining wall construction.

Wall 119, located along the westbound side of Route 91, was part of the larger Highway 60/91/215 Freeway Improvement Project, while Wall 207 was situated on the east side of the northbound lanes of Interstate 215, near the Chicago Avenue overpass. Both walls were classified as Type 1 retaining walls and were incorporated into the Route 91 widening project. Wall 119 was constructed in 2003, and Wall 207 followed in 2006, under the joint effort between Caltrans and CIWMB. In both projects, TDA was utilized as a lightweight alternative to traditional soil backfill. Wall 119 incorporated approximately 83,700 End of life tires behind 300 feet of the retaining wall. Meanwhile, Wall 207 used 1,410 tons of TDA, equivalent to 141,000 End of life tires, over a similar distance of 300 feet. A geotextile wrap was applied to prevent soil infiltration into the TDA, with an additional two feet of cover soil placed over the TDA backfill.

The primary goal of these projects was to demonstrate that using TDA could reduce the soil pressure exerted on the retaining wall by 30 percent. Monitoring instruments were installed during construction to measure the wall's response compared to a conventional retaining wall with soil backfill. The results showed that the TDA significantly reduced the pressure on the wall, enabling an

alternative design that required less concrete and steel, thereby lowering construction costs.

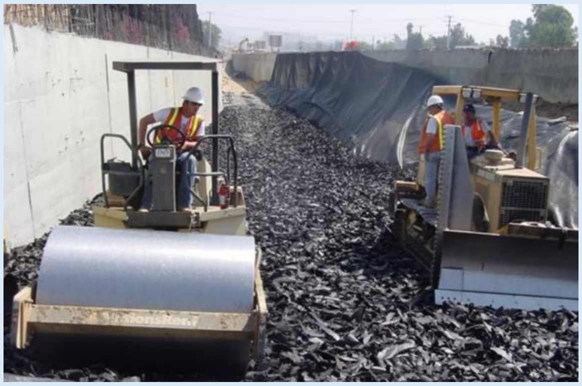


Figure 8.1: Placement of the TDA using conventional construction equipment during the construction.

8.1.2 Mechanically Stabilized Earth (MSE) Wall, the I-80/94 Interchange Modification Project (IR 29901, Wall No. 54), Indiana

The Indiana Department of Transportation (IDOT) utilized a TDA/sand mixture, consisting of 25% TDA by weight, as a lightweight backfill for a 10-foot-tall mechanically stabilized earth (MSE) wall during the I-80 highway widening project in northwest Indiana. This wall, which was constructed to span over 40 feet of weak riverbed soils, incorporated metal straps as reinforcement (Balunaini & Prezzi, 2010; Prezzi & Duvvuru Mohan, 2011)). The construction process began with the installation of a bottom aggregate layer, a wall levelling pad, and the initial set of wall panels. The TDA/sand mixture was subsequently spread using a dozer, compacted in 12-inch layers with a 10-ton smooth-drum roller, and covered with expanded polystyrene (EPS) blocks. The final steps included placing an aggregate base and laying concrete pavement. Settlement measurements, inclinometers, survey points, and crack gauges were employed to monitor the performance of the MSE wall. The monitoring results indicated a vertical movement of only 0.12 inches and a horizontal displacement of less than 0.05 inches.

Figure 8.2: Mixture spreading in lifts of 12 inches using a bulldozer.

8.1.3 Merrymeeting Bridge Abutment, Topsham, Maine

TDA was used to backfill the abutment of the bridge located in Topsham, Maine (Humphrey et al.,2000). The foundation soil at the site consisted of a sequence of soft marine silt and sand and soft marine clay extending to depths of 50 ft (15.24 m). The existing slope at the site had a safety factor of approximately 1.0, indicating a high risk of deep-seated failure. To stabilize the slope, the design engineer decided to use lightweight fill material. TDA was the most economical choice compared to alternatives like Geofoam® and expanded shale aggregate. This decision also contributed to the recycling of 400,000 scrap tires. The design involved partially excavating the slope and placing 14 feet of TDA, followed by a 6-foot soil layer. A longitudinal cross-section of the bridge abutment is presented in Figure 8.3. The use of TDA for backfilling the bridge abutment met the project's objectives, demonstrating its cost-effectiveness, ease of application, and environmental benefits in geotechnical construction.

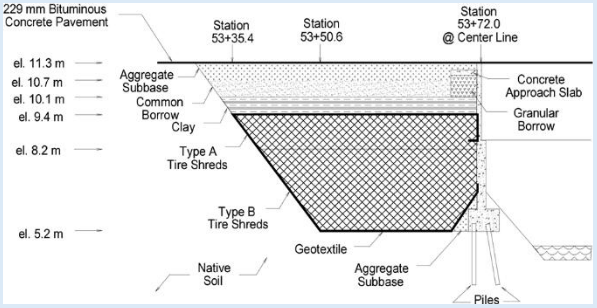


Figure 8.3: Longitudinal cross-section of the bridge abutment (Humphrey et al., 2000).

8.1.4 Geysers Road, Sonoma County, California

A landslide impacted a section of Geysers Road in Sonoma County In the winter of 2006. Intense rainfall led to fully saturated soils, and the combination of the saturated ground and an inadequate road drainage system likely triggered the landslide. As a result, an 80 m stretch of the road required repairs. Figure 5.4 shows the landslide damage. Consequently, in 2008, CalRecycle collaborated with Sonoma County to address the damage, choosing TDA as a lightweight fill to help prevent further landslide issues. The repair involved placing two layers of TDA wrapped in geotextile, with a layer of low-permeability soil between them. Another layer of low-permeability soil was added on top of the upper TDA layer, followed by a soil backfill layer, which served as the road's subgrade. Figure 5.5 shows the schematic design of the repair, while Figures 8.6 and 8.7 show the placement of the TDA on the geotextile fabric during construction and the completed Geysers Road project after TDA installation. This repair scheme resulted in a smaller excavation and a lower-cost repair. This project used approximately 150,000 End of life tires and resulted in an overall cost savings to the county of $370,000.

Figure 8.4: The landslide damage.

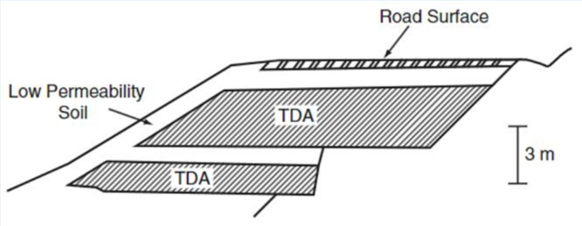


Figure 8.5: Schematic design of the repair.

Figure 8.6: Placement of the TDA on the geotextile fabric during construction.

Figure 8.7: The completed Geysers Road project after TDA installation.

8.1.5 The SR-110 Road Widening Project, Marshall County, Indiana

The Indiana Department of Transportation (IDOT) used a lightweight TDA-Sand mixture in a road widening project in 2008. The SR-110 in Marshall County required an elevation increase over peat. accordingly, a lightweight fill composed of a 35% TDA and 65% sand mixture (by weight) was chosen to minimize the anticipated settlement (Prezzi, 2009). The TDA/sand mixture was placed over a geogrid and geotextile fabric layer. The material was spread using a dozer and compacted in 12-inch layers with a 5-ton smooth-drum roller. A geotextile fabric was placed over the TDA/sand mix in the side slope areas, followed by 6 to 12 inches of topsoil. Only geogrid was used above the TDA/sand mixture for the pavement areas, beneath 9 inches of aggregate base and an unspecified thickness of bituminous pavement. 710 tonnes of tire shreds were used in this project. Settlement monitoring recorded 0.6 to 1 inch of settlement during the first 100 days after the roadway was opened to traffic.

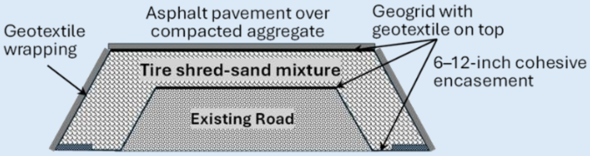


Figure 8.8: Cross-section of the embankment at SR110 (after Samadi 2013).

Figure 8.9: Loader bucket used to mix shredded tires and sand thoroughly.

Figure 8.10: Mixture spread in lifts of 12 inches using a tracked bulldozer.

8.1.6 Reconstruction of Route 17 in the Towns of Windsor and Kirkwood, Binghamton, New York.

In 1997, the New York State Department of Transportation (NYDOT) launched a pilot project to evaluate the use of TDA as embankment fill material. The goal of this initiative was to establish guidelines and specifications for incorporating TDA in future civil engineering projects. This project involved constructing a 200-meter-long embankment section in the summer of 1999, which incorporated approximately 2,500 metric tons of tire shreds as the core material. The tire-shred layer reached a maximum thickness of 3 meters, with an additional 1.5 meters of embankment fill covering the top and 1.0 meter along the sides as shown in Figure 5.11. The entire section was further surcharged with 1.25 to 2.50 meters of additional fill. After four months, the surcharge was removed to the subgrade level, a granular base was installed, and the section was paved. The design of this prototype embankment was consistent with standard roadway embankments and incorporated sufficient safety factors to mitigate risks such as base sliding, bearing capacity issues, and slope failure. The project followed guidelines issued by the Federal Highway Administration to prevent internal heating of tire-shred embankments. The contractor utilized typical construction equipment. The TDA was placed in the fill using a front-end loader and was compacted with a smooth-drum roller. Extensive instrumentation was installed and monitored during and after construction. The settlement behaviour of the embankment aligned with expectations from previous similar projects, and temperature monitoring confirmed no internal heating of the tire shreds.

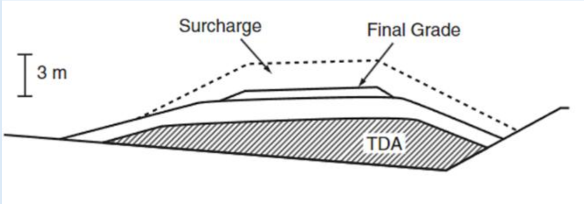


Figure 8.11: Schematic of TDA fills for Reconstruction of Route 17 project, Binghamton, New York (Dickson et al., 2001).

Figure 8.12: TDA spread in lifts of 12 inches.

8.1.7 Los Angeles County Area Landfill, Los Angeles County, California.

TDA was utilized for landfill gas collection trenches in the Los Angeles County Area Landfill. The gas collection system used standard piping, but instead of traditional rock aggregate, Type A TDA was selected as a replacement. The process started by excavating a 3-by-3-foot trench into the existing waste, which was then moved to the active landfill area. Then, a six-inch layer of TDA was placed at the bottom of the trench as a foundation for the pipe (see Figure 8.13). Once the landfill gas collection pipe was installed, an additional 12-inch layer of TDA was added on top. The TDA was then covered with geotextile material, and the remaining portion of the trench was filled with cover soil. Figure 8.14 shows the gas collection pipeline covered in TDA material.

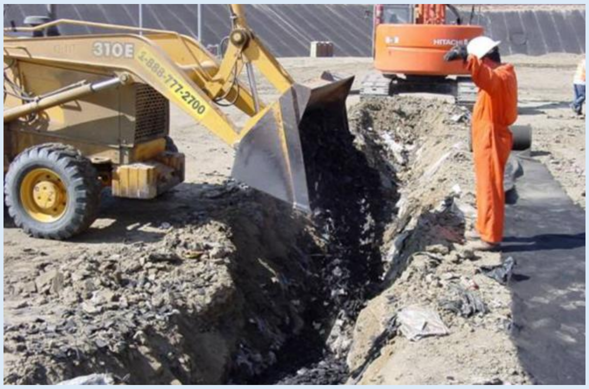


Figure 8.13: TDA was placed at the bottom of the trench as a foundation for the pipe.

Figure 8.14: The gas collection pipeline covered in TDA material.

8.1.8 BFI Rockingham Landfill Project, Rockingham, Vermont.

The DSI Superfund Landfill, also known as the BFI Rockingham Landfill, is located in Rockingham, Vermont. It was initially listed as a Superfund site in 1988 due to contamination concerns. The site spans approximately 17 acres and was used for solid waste disposal. Over time, environmental issues, including the contamination of groundwater with hazardous substances like arsenic and lead, led to its designation as a Superfund site by the U.S. Environmental Protection Agency (EPA). The EPA has since implemented various cleanup efforts, including the installation of systems to collect gas and manage leachate. TDA was used as a drainage cover layer at this site as a part of a multilayer cap consisting of several layers, including a gas vent layer, a compacted low permeability native soil layer, and a very low density polyethylene geomembrane (Andrews and Guay, 1996). The original design specified a 300 mm thick sand layer for drainage, requiring approximately 21,400 m^3 of material. TDA was considered as a cost-effective alternative to sand. However, due to the limited availability of TDA near the site, it was used only on part of the landfill, while sand was utilized for the remainder. This allowed for a comparative assessment of the performance between the two materials. The EPA conducts regular Five-Year Reviews to ensure that the implemented remediation measures continue to protect human health and the environment. The latest review concluded that the cleanup efforts remain effective, though some recommendations for additional measures were made to further address groundwater contamination. Figure 15 shows an aerial photo of the BFI Rockingham Landfill.

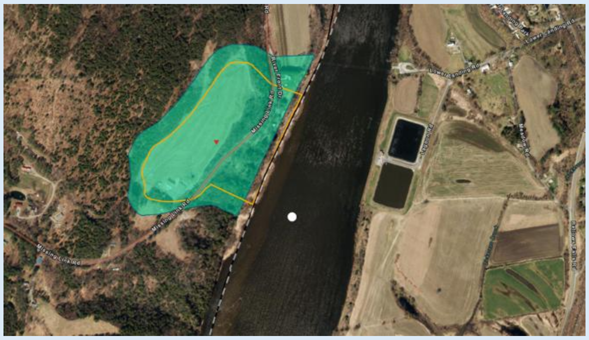


Figure 8.15: An aerial photo of the BFI Rockingham Landfill (Andrews & Guay, 1996).

8.1.9 Bay Area Rapid Transit (BART) Fremont Warm Springs Extension Light-Rail Project, Fremont, California.

TDA was used as a subballast layer to mitigate ground-borne vibrations in a section of the track of the Fremont Warm Springs extension light-rail project in Fremont, California.

The tracks requiring vibration control were situated close to residential areas and crossed the Hayward Fault. TDA was selected for this project due to its proven effectiveness in reducing vibrations. Additionally, the cost of constructing the track with TDA was estimated at approximately $121 per foot, significantly lower than the $600 to $1,000 per foot cost for alternative vibration mitigation methods. The contractor employed common construction equipment for the project. TDA was placed using a front-end loader and compacted with a smooth-drum roller, as shown in Figure 5.16.

Figure 8.16: TDA was placed using a front-end loader and compacted with a smooth-drum roller.

8.2 Canada

8.2.1 St. Stephen Route 1 Reconstruction Project, St. Stephen, New Brunswick.

A significant embankment failure occurred in 2006 during the construction of a highway embankment in St. Stephen, New Brunswick. The incident affected a 140-meter-long section of the approach embankment leading to the Dennis Stream bridge crossing. At the time of the failure, the embankment stood approximately 12 meters high. The primary cause of the failure was the presence of soft marine clay in the foundation soil coupled with the rapid loading of the embankment due to the expedited construction activities. As illustrated in Figure 8.17, the failure was characterized by a relatively deep-seated circular slip, accompanied by some lateral spreading.

Figure 8.17: The St. Stephen embankment failure (after Mills et al., 2015).

Understanding the failure mechanism allowed for the exploration of various remedial solutions to reconstruct the embankment to its original design height. Restoring this height was critical due to the fixed elevation required by the Dennis Stream Viaduct, located about 225 meters to the west, and the Valley Road Overpass, situated 100 meters to the east of the failure site. The remediation strategy involved a two-stage construction process, utilizing prefabricated vertical drains in the underlying clay and incorporating two layers of Type B tire-derived aggregate (TDA), each 10 feet thick, fully encapsulated in woven geotextile. The TDA was topped with a minimum of 3 feet of low-permeability soil, with an additional 7 feet of final cover in the paved areas. The use of TDA in this project offered a significant cost advantage, saving the New Brunswick Department of Transportation (NBDOT) approximately 30% compared to the next viable option, which was stone columns. In addition to the economic benefits, the project also provided substantial environmental advantages by repurposing around 1.6 million scrap tires, equivalent to approximately two years' worth of discarded tires generated in the province of New Brunswick. Settlement measurements, inclinometers, survey points, and crack gauges were employed to monitor the performance of the embankment. The monitoring results from 10 years after completion indicated excellent performance.

Figure 8.18: TDA was placed in 12-inch lifts using a front-end loader and compacted with a smooth-drum roller (after Mills et al., 2015).

Figure 8.19: The completed St. Stephen embankment (after Mills et al., 2015).

8.2.2 Boundary Road Embankment Project, Cornwall, Ontario.

The Ontario Ministry of Transportation (MTO) used TDA in Eastern Ontario as part of an embankment being built for a new bridge across Highway 401 at Boundary Road just east of Cornwall. Boundary Road is a frequently used route, mainly by trucks accessing Highway 401. The area around it features a mix of rural landscapes along with commercial and industrial developments. Along the southern stretch of Boundary Road, near Highway 401, there are service stations, truck repair shops, and recreational vehicle centers. The north and south embankments were partially built with a tapered, three-metre-thick layer of TDA, with sizes generally ranging between 12 mm (0.5 inches) and 305 mm (12 inches). Each TDA layer is wrapped in geotextile and covered with low-permeability cover soil. The volume of the used TDA fill was 4,000 m^3. As a result, the Boundary Road project used around 400,000 shredded tires from a registered TDA processing plant less than 50 km from the site.

The contractor used standard construction equipment, and the construction process went without major issues. The TDA was placed in the fill using a D5 front-end loader and was compacted with six passes of vibratory steel drum roller for maximum compaction. Figure 5.20 shows the TDA placement process in 12 inches layers at the north embankment. Two metres of impervious clay bed and geotextile cover were used to encase the TDA within the designed framework to limit air and water infiltration. There are also several granular drains to remove any water that does get in. Below the layer are two metres of borrow material. Extensive field monitoring instrumentation was included in the project to help monitor the TDA at all phases of the construction process and for post-evaluation of the TDA's environmental and geotechnical performance. This was necessary not only because it was the first of its kind in Ontario but also in order to analyze any iron and manganese that leeched out of the tires. The leak potential was not extreme enough to violate the province’s water protection policy. In October of 2012, the embankments were built – the area was open to the public one month later.

Figure 8.20: TDA was placed using a front-end loader and compacted with a smooth-drum roller (photo provided by Mr. Sangiuliano, MTO).

Knowledge Gaps

9. Knowledge Gaps and Future Research Directions

The knowledge gap in the research on tire-derived aggregates in civil engineering applications primarily involves several aspects:

9.1 Long-Term Behavior and Durability

The long-term performance of TDA, especially when exposed to natural weathering processes, is not comprehensively documented. Research lacks extensive data on how factors like UV radiation, moisture absorption, and freeze-thaw cycles affect TDA properties over time. Long-term durability is critical for evaluating the lifespan of TDA-based construction materials.

9.2 Environmental Impact

While TDA use is touted for its sustainability benefits, more research is needed to quantify and compare the life cycle environmental impacts of TDA relative to conventional aggregates. This includes assessing the potential leaching of chemicals and their effects on soil and groundwater quality in scenarios different from those considered, for example, in extremely hot and arid climates.

9.3 Further Investigation of the Thermal Properties

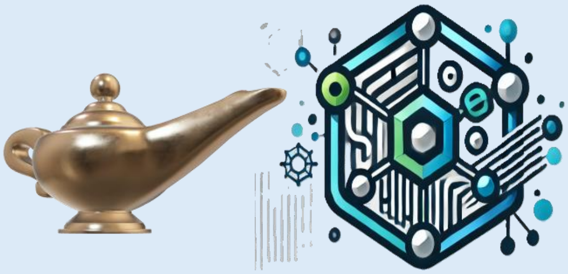
While some studies have investigated the mechanical properties of TDA, like compressive strength and durability, there is still a limited understanding of the thermal expansion characteristics of TDA under different environmental conditions. This information is crucial for assessing the suitability of TDA in climates with significant temperature fluctuations.

9.4 Standardization and Best Practices

There is a lack of standardized design guidelines or best practices for using TDA in specific civil engineering applications. While its use has been successfully demonstrated in several projects, there is still a need for more robust guidelines on the use of TDA, including optimal mix proportions, compaction requirements, and quality control measures for its integration into construction projects.

9.5 Fostering Novel Applications of TDA

Additional research is needed to foster novel applications of TDA, especially in the geoenvironmental field, where its excellent environmental properties can be utilized. Further investigation should focus on TDA's potential as an adsorbent, filter medium, and support medium for microbial growth. TDA might also be effective for removing emerging contaminants.



9.6 Field Performance Data

Many studies on TDA are laboratory-based, and the field performance data remains limited. More in-situ monitoring and long-term field evaluations are necessary to validate the results obtained in controlled environments and to assess the real-world performance of TDA in civil engineering infrastructure.

Conclusions and Recommendations

10. Conclusions and Recommendations

The increasing demand for sustainable practices in civil engineering has prompted a reevaluation of traditional materials and methods, leading to the exploration of innovative alternatives such as tire-derived aggregate. TDA presents a multitude of advantages that align with contemporary environmental goals, particularly in reducing waste and minimizing ecological footprints. Its lightweight properties, enhanced drainage capabilities, and ability to alleviate structural stresses position TDA as a valuable resource in diverse applications, including lightweight fill material for embankments and retaining walls, in septic system drain fields, backfill above and around pipes, and as shock absorption layers in vibration control applications and railway infrastructure. Research indicates that TDA exhibits low leaching rates of potentially harmful compounds, thereby affirming its environmental safety for civil engineering applications.

TDA is particularly beneficial for embankments built on weak soils like soft marine clays. Its lightweight, interlocking properties and high shear strength help control settlements and reduce imposed stresses, improving structural integrity and safety. In addition, its thermal insulation, freeze-thaw mitigation, high permeability, and excellent drainage capabilities improve long-term performance.

Likewise, TDA can significantly enhance the mechanical properties and stability of soils used in slope stabilization. Integrating TDA with other materials like lime, waste rock, and silica has been shown to further improve its efficacy, offering a sustainable and effective solution for slope stabilization challenges.

Using TDA in freeze-thaw prevention projects presents a promising strategy to improve the durability and performance of civil infrastructure. The material's unique characteristics, including low density, thermal insulation, and resilience, make it highly effective in mitigating the effects of freeze-thaw cycles. Integrating TDA can lead to longer infrastructure lifespans and lower maintenance costs, offering a sustainable alternative to conventional approaches.

The use of TDA in shallow foundation applications presents a promising and environmentally sustainable alternative to traditional materials. Several studies and real-world applications have demonstrated the potential of TDA to provide cost-effective, durable, and environmentally friendly foundations.

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