Tire Derived Aggregate – Recycled Engineered Material for MTO Highway Embankment Construction

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ABSTRACT
MTO is constructing highway embankments at the Boundary Road / Highway 401 interchange in Cornwall, Ontario using Tire Derived Aggregate (TDA) processed from approximately 400,000 scrap tires. TDA is a recycled material processed from scrap tires into chips and shreds generally between 12 mm and 305 mm in size and intended for use in civil engineering applications. Use of TDA as a recycled engineered material will reduce the requirement for natural soil and rock materials from pits and quarries and divert scrap tires from stockpiles, landfills and incineration and their associated environmental hazards. The purpose of this project is to demonstrate the engineering and environmental benefits of using TDA as a recycled non-traditional construction material. Based on the results of this project, MTO will pursue future applications of TDA in Ontario for highway construction.

RÉSUMÉ
Le MTO est la construction des remblais d'auto routes au chemin Boundary / route 401 à Cornwall, en Ontario, en utilisant Tire Derived Aggregate (TDA) transformés à base de près de 400.000 pneus usés. TDA est un matériau recyclé transformés à base de vieux pneus en copeaux et des lambeaux généralement comprise entre 12 mm et 305 mm en taille et destinés à être utilisés dans des applications de génie civil. L'utilisation de TDA en tant que matériau recyclé conçu permettra de réduire l'exigence de sol naturel et les matériaux rocheux de mines et de carrières et de détourner les pneus usagés provenant des stocks, les sites d'enfouissement et l'incinération et de leurs risques environnementaux associés. Le but de ce projet est de démontrer les avantages techniques et environnementales de l'utilisation de TDA en tant que matériau de construction non traditionnelles recyclées. Sur la base des résultats de ce projet, MTO poursuivra les applications futures de TDA en Ontario pour la construction routière.

1 INTRODUCTION

The Ontario Ministry of Transportation (MTO) proposes to use Tire Derived Aggregate (TDA) as a recycled engineered material to construct highway embankments at selected locations in Ontario. The first location selected by MTO is the interchange at Boundary Road and Highway 401 in Eastern Ontario, Cornwall.

For this project, TDA processed from approximately 400,000 scrap tires will be placed as mass embankment fill up to 3 metres thick within the core of approach embankments for the new replacement bridge taking Boundary Road over Highway 401. TDA embankment construction is scheduled for mid-2011.

An estimated 12 million used tires are generated annually in Ontario and there are approximately 2 to 3 million tires stockpiled across Ontario (MOE 2009). Stockpiled tires are a potential fire hazard (e.g., Hagersville Tire Fire in 1990) and a potential breeding area for disease-carrying insects (e.g., West Nile Virus). The emissions produced by burning tires pose serious environmental and human health threats. Scrap tires occupy valuable air space in landfill sites.

TDA has beneficial properties for highway construction and has been successfully used as engineered fill in other jurisdictions since the early 1990's, including several states in the U.S. For a recent TDA project in New Brunswick, NBDOT used TDA processed from about 1.4 million scrap tires as lightweight fill for reconstruction of a failed highway embankment on a new portion of Route 1 near St. Stephen (Mills and McGinn 2008, 2010).

Due to the environmental concerns associated with scrap tires and the beneficial properties of TDA, the MTO is pursuing use of TDA as a recycled engineered material for highway construction in Ontario.

2 MATERIAL

Tire Derived Aggregate (TDA) is a recycled engineered material. ASTM D6270-08 (2008) defines TDA as pieces of scrap tires that have a basic geometrical shape, generally between 12 mm and 305 mm in size and are intended for use in civil engineering applications. See Figures 1 and 2.

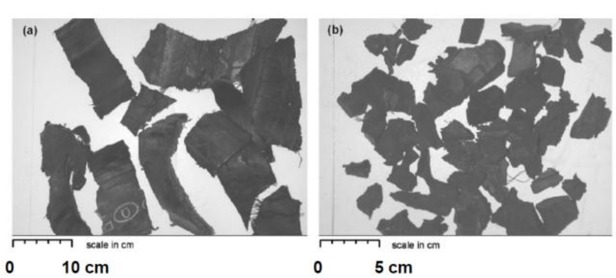

Figure 1. Tire shreds and chips (Wartman et al. 2007)

Figure 2. Tire Derived Aggregate (photo by D. Staseff)

Fixed and mobile shredders are used to produce TDA from scrap tires using a mechanical shearing process with sharp rotating blades.

A cubic metre of compacted TDA fill contains the equivalent of approximately 100 processed scrap tires.

2.1 Engineering Properties of TDA

TDA has the following beneficial properties for civil engineering applications (ASTM 2008, Humphrey 2005 and 2009):

- Lightweight – compacted unit weight (±8 kN/m^3) about one-third of compacted soil;
- Low lateral pressures on retaining walls – as low as half of conventional soil backfill;
- Good thermal insulator – about 7 to 8 times higher thermal resistance than granular soil;
- Free draining due to high hydraulic conductivity, generally > 1 cm/s;
- Compressible and absorbs vibrations; and
- Non-biodegradable.

ASTM (2008) provides typical material properties for TDA based on results from several laboratory and field studies.

2.2 Civil Engineering Applications for TDA

Use of TDA in civil and geotechnical engineering applications include the following (ASTM 2008, Humphrey 2009):

- Lightweight fill or mass embankment fill;
- Backfill for retaining walls and bridge abutments;
- Drainage layers for roads, landfills and septic fields;
- Thermal insulation to limit frost penetration beneath roads and to limit heat loss from buildings;
- Vibration damping layers for rail lines; and
- Landslide stabilization.

Embankment fill material for highway construction normally consists of an approved earth or granular borrow material with gradation specifications. A lightweight fill material may be required in the case of soft and compressible foundation soils where settlement and stability are of concern. A layer of TDA up to 3 m thick can replace conventional soil materials or other lightweight fill materials within the embankment core, as shown in Figure 3.

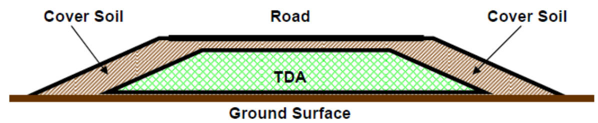

Figure 3. Conceptual TDA Embankment Fill

TDA fills must be designed to minimize the possibility of an internal heating reaction caused by oxidation of exposed steel belts and rubber. Design guidelines in ASTM D6270-08 (2008) are provided to minimize the possibility for self-heating of TDA fills by minimizing factors that could create conditions favourable for this reaction, including free access to air and water:

- Maximum individual TDA layer thickness of 3 m.
- The top and sides of the TDA fill should be covered with a layer of low permeability soil with $\geq$ 30% fines in order to minimize infiltration of water and air into the TDA and to prevent direct contact between TDA and soil containing organic matter, such as topsoil.

2.3 Technical Standards

ASTM D6270-08 is entitled "*Standard Practice for Use of Scrap Tires in Civil Engineering Applications*" (ASTM 2008). The standard provides testing procedures, material characterization, design considerations, construction practices and leachate generation potential for use of processed scrap tires, in place of conventional stone, gravel, sand, soil and other fill materials.

The standard was originally developed in the late 1990s to address the problem of internal heating within thick TDA test fills constructed in the U.S. in the mid-1990s. Past concerns that thick TDA fills could self-combust have been addressed in the ASTM standard by restricting individual TDA layer thickness for embankment fills to 3 metres and specifying the gradation and quality of the tire shreds. Since the mid-1990s, there have been over 100 TDA fills constructed in North America with a thickness less than 3 metres and with no evidence of a deleterious heating reaction (ASTM 2008).

Two classes of TDA fills are specified in ASTM D6270-08: Class I Fills with TDA layers < 1 m thick and Class II Fills with TDA layers ranging from 1 m to 3 m thick. Class II fills must be constructed to minimize infiltration of water and air.

Material specifications for two size ranges of TDA are specified in ASTM D6270-08. Type A is suitable for drainage, vibration damping and insulation applications. Type B is suitable for embankment fill, retaining wall backfill and some landfill drainage and gas collection applications.

Further details and a comprehensive list of references are found in ASTM (2008).

2.4 Environmental Effects

TDA is not classified as a hazardous waste (ASTM 2008). Based on several laboratory and field studies conducted to support ASTM D6270-08, TDA has a negligible off-site effect on water quality.

According to Humphrey and Swett (2006), TDA leachate has a limited effect on drinking water quality and fresh water aquatic toxicity for a range of civil engineering land applications. Specific conclusions are:

- TDA is unlikely to increase the concentration of substances with primary drinking water standards above those naturally occurring in the groundwater.
- It is likely that TDA will increase the concentration of iron and manganese to secondary standards (non-health related), but the data indicates that these elements have limited ability to migrate away from the TDA installation.
- TDA placed above the groundwater table has negligible toxic effects for fresh water aquatic organisms.

2.5 Legislation and Regulations

Regulatory requirements for use of TDA vary depending on the jurisdiction. According to Ontario Regulation 347 (General Waste Management) under the *Environmental Protection Act* (EPA), used tires that have not been refurbished for road use are a designated waste in Ontario. Section 6 of Reg. 347 establishes the regulatory requirements for used tire management in Ontario and states that sites with 5,000 or more tire units require a Certificate of Approval (C of A) from the Ministry of the Environment (MOE) under Part V of the EPA. Land application of shredded or chipped tires as an engineered fill is not exempt from Part V of the EPA and Reg. 347.

Due to these regulatory barriers and lack of an engineered fill policy or regulation, use of scrap tires for civil engineering applications, such as embankment fill and structure backfill, have not yet developed in Ontario.

3 BOUNDARY ROAD / HIGHWAY 401 PROJECT

3.1 Site Selection

In response to used tire initiatives from Waste Diversion Ontario (WDO) and Ontario Tire Stewardship (OTS), MTO initiated a site selection process in 2009 for use of TDA as mass engineered fill to construct highway embankments in Ontario. MTO Regions were requested to identify sites that met specific site-selection criteria. The Boundary Road / Highway 401 site was chosen as a preferred site for the following reasons:

- Favourable subsurface and groundwater conditions.
- No issues regarding embankment stability and settlement.
- The site is not an environmentally sensitive area.
- The TDA approach embankments are on a secondary roadway.
- The site is situated in close proximity to a registered TDA processing plant less than 50 km away.
- The schedule for the project was favourable because construction was to commence in 2010/11.
- The project required sufficient quantities of TDA embankment fill that would enable about 400,000 scrap tires to be recycled.

3.2 Site Location

The proposed location of the first MTO TDA project is the interchange at Boundary Road and Highway 401 in Cornwall, southeast Ontario. See Figures 4, 5 and 6.

Figure 4. Site Location – Eastern Ontario (Natural Resources Canada Map)

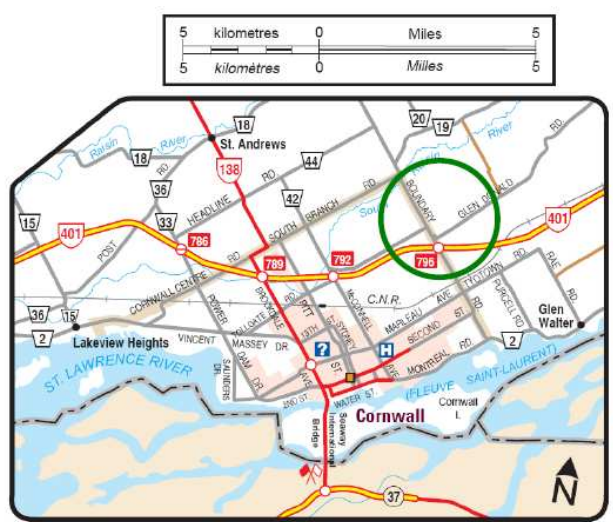

Figure 5. Boundary Road / Highway 401 Site – Cornwall (Road Map Ontario - MTO Internet)

Boundary Road is a well-travelled route, especially with truck traffic accessing Highway 401. The surrounding landscape is rural with commercial and industrial development. Service stations, truck repair and recreational vehicle centres are located along Boundary Road to the south of Highway 401. A large distribution centre is situated in the industrial park to the southwest. A cement plant and a logistics company occupy sites to the north of Highway 401. An abandoned CPR right-of-way crossing Boundary Road north of Highway 401 is currently in use as an ATV recreational trail.

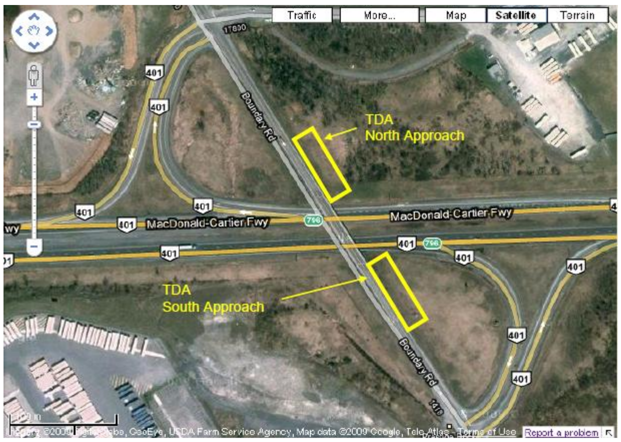

Figure 6. Approximate TDA Fill Areas (Google Map)

Under MTO Contract No. 2010-4003 (MTO 2010), TDA will be placed as mass embankment fill within the core of the approach embankments for the new replacement bridge structure to carry Boundary Road over Highway 401 on the east side of the existing bridge. The abutments for the new two-span bridge will be founded on driven piles and the pier founded on concrete caissons end bearing on competent glacial till and bedrock.

3.3 Subsurface Conditions

A geotechnical investigation was conducted at this project site by Coffey Geotechnics Inc. in 2008. According to Coffey (2009), the site is located within the physiographic region known as the Glengarry Till Plain and the bedrock underlying this area consists of Middle Ordovician limestone and shale.

The fieldwork consisted of drilling and sampling eight boreholes – F1 to F8. The plan locations of the boreholes are shown on Figure 7 and a stratigraphic section is shown on Figure 8.

Boreholes F3 and F7 were advanced from the Boundary Road surface level from elevation 63.3 m and 63.0 m. The remaining boreholes were drilled from the Highway 401 level from elevations ranging from 59.5 m to 56.4 m. The boreholes encountered the following subsurface materials:

- Veneer of topsoil and/or various fill materials, including existing embankment fills;
- Surficial native soils consisting of clayey silt, sandy silt and gravely sand;
- Sandy silt to silty sand till; and
- Argillaceous limestone bedrock at about 6 m to 8 m below the Highway 401 level or at elevation 49.4 m to 50.8 m.

Groundwater conditions in the boreholes were observed during drilling and upon completion in the open boreholes. A piezometer was installed in each of Boreholes F2 and F6 to enable groundwater level monitoring. Groundwater level below original grade at the time of the investigation was measured at about elevation 56 m to 57 m.

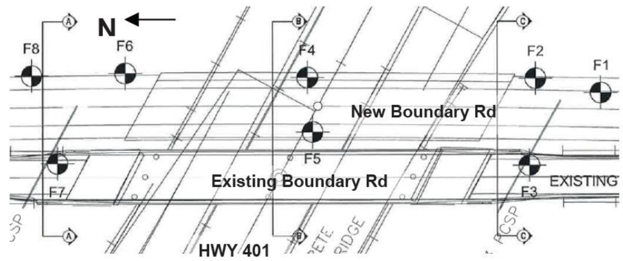

Figure 7. Borehole Locations (Coffey 2009)

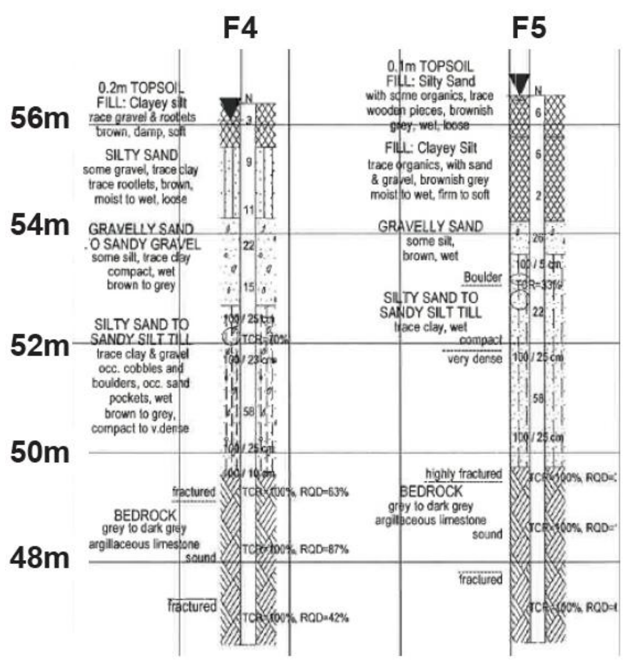

Figure 8. Stratigraphic Section (Coffey 2009)

3.4 Approvals

In January 2010, MTO applied for a Certificate of Approval (C of A) from MOE for this TDA construction project. Following public consultation and technical review, a C of A was issued to MTO in May 2010. Key conditions include a groundwater monitoring program and a final report with monitoring results, interpretations, conclusions and recommendations for future use of TDA as a recycled engineered material in Ontario.

3.5 Design

MTO proposes to construct Class II Fills with Type B TDA shreds at the Boundary Road / Highway 401 project site. TDA will be placed in two separate fill areas up to 3 m thick within the north and south approach embankments for the new replacement bridge taking Boundary Road over Highway 401. Each TDA layer will be wrapped in geotextile and covered with low permeability cover soil.

Approximate horizontal limits of the TDA embankment fills are shown in Figure 6. Total TDA in-place volume is approximately 3,850 m^3. Total TDA quantity is approximately 3,000 tonnes.

The TDA fill areas are designed to not encroach on any swamps, wetlands or surface water courses identified during the environmental planning process. The design includes the following minimum vertical and horizontal separations and setbacks to be maintained between the TDA and the following features:

- 2 m – groundwater table;
- 30 m – surface waterbody, water course, swamp, wetland;
- 100 m – potable groundwater well.

Staging areas may be located on-site by the contractor for receipt and temporary stockpiling of TDA prior to placement and compaction within the fill areas. Ontario Fire Code requirements apply for above-ground temporary storage of TDA tire shreds.

Detailed design of the TDA embankments was administered by MTO Eastern Region to deliver the design drawings and specifications in 2010. The project team included MTO Foundations Office, MTO Eastern Region, Prime Consultant (AECOM), Foundations Engineering Consultant (Coffey Geotechnics Inc.) and a TDA Design Consultant (Dr. D. N. Humphrey - University of Maine).

The following design guidelines were used to incorporate TDA into this project (ASTM 2008, Humphrey 2010, MTO 2010):

- The maximum thickness of any single layer of TDA does not exceed 3 m in accordance with ASTM D6270-08 to limit internal heating potential of TDA.
- A separation layer between the TDA and the original ground comprised of earth borrow provides separation between the bottom of the TDA and the groundwater.
- The bottom of the TDA layer is sloped 3% toward the outside (east) edge of the embankment to promote outward flow of water that infiltrates through the TDA.
- Granular drains are located 25 m on centre. The drain has a cross section of 600 mm thick by 600 mm wide and is sloped 3% toward the outside slope.
- The minimum thickness of TDA is set to about 1 m. TDA thickness less than 1 m does not warrant the added construction effort and the cost of the geotextile that surrounds the TDA.
- The ends of the TDA zone are tapered in a longitudinal direction at a slope of 2H:1V to zero thickness.
- The TDA is wrapped in geotextile to separate TDA from the cover soil and to minimize infiltration of the surrounding soil into the voids between the TDA shreds. The geotextile can be woven or non-woven.
- The horizontal width of soil cover on the outside (east side) of the TDA is 4 m to provide an area wide enough for soil placement and compaction using conventional construction procedures.
- The cover material is a modified earth borrow material with minimum of 30% passing the 75 μm sieve size to prevent air and water infiltration into the TDA.
- The top of the TDA layer at any given station is horizontal to simplify construction.
- The distance between the road surface and the top of the TDA layer, as measured at the embankment centerline, is at least 2 m to limit deflections of overlying pavement caused by traffic loading. This is somewhat thicker than typical projects but is justified for the Boundary Road project to minimize the influence of one side of the TDA zone resting on the east side slope of the existing embankment. Moreover, the lightweight characteristics of the TDA are not important for this project so there is no need to minimize weight by minimizing the thickness of soil used in the embankment.

A typical TDA cross-section is shown in Figure 9.

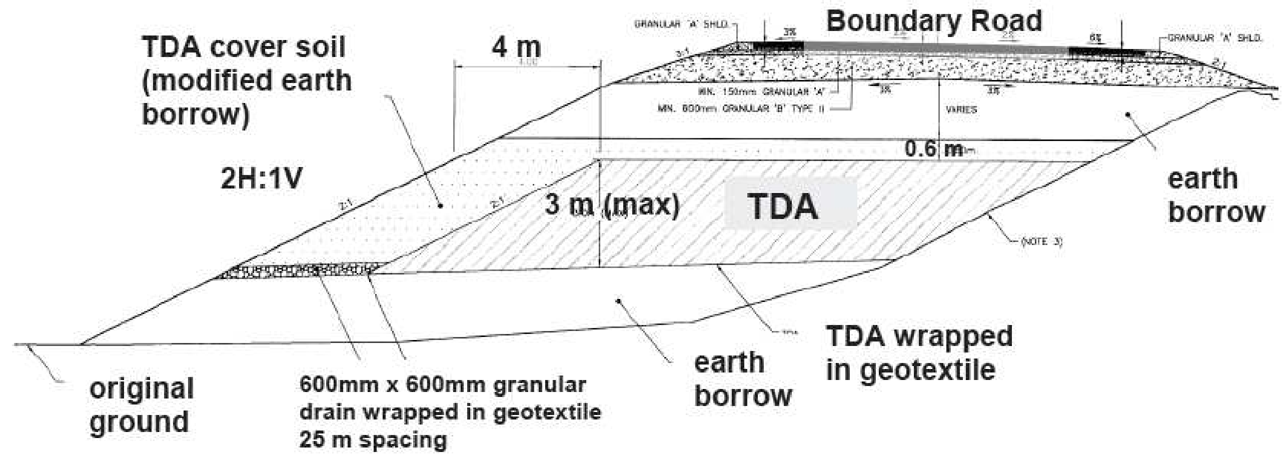

Figure 9. Typical TDA Cross-Section (MTO 2010)

Figure 9 illustrates the TDA layer sandwiched between the underlying borrow material and the overlying TDA cover soil, specified as modified borrow material with a minimum 30% passing the 75 μm sieve size. The horizontal drains and the geotextile that encapsulate the TDA are also shown in the typical cross-section.

In customizing the design for the Boundary Road project, the guidelines above were applied in addition to the project specific MOE C of A requirements, including separation of 2 m between the bottom of the TDA and the groundwater table (minimum elevation of 58 m for the bottom of TDA was determined for the north fill area) and the minimum setbacks from waterbodies and potable groundwater wells.

At the north approach, the TDA limits extend from stations 9+880 to 9+950 or a length of 70 m. The height of the embankment to the north of the bridge at station 9+950 is about 7.5 m. The embankment height decreases at increasing distance north from the bridge. Applying the general guidelines and project specific requirements, only a single TDA layer up to 3 m thick was feasible.

At the south approach, the TDA limits extend from stations 10+050 to 10+108 or a length of 58 m. The height of the embankment at station 10+050 is about 6 m. The embankment height decreases with increasing distance south from the bridge. Applying the general design guidelines and project specific requirements, a single TDA layer up to 3 m thick was the only feasible option.

Figure 10 illustrates the longitudinal profile for the north approach embankment and the vertical and longitudinal limits of the TDA:

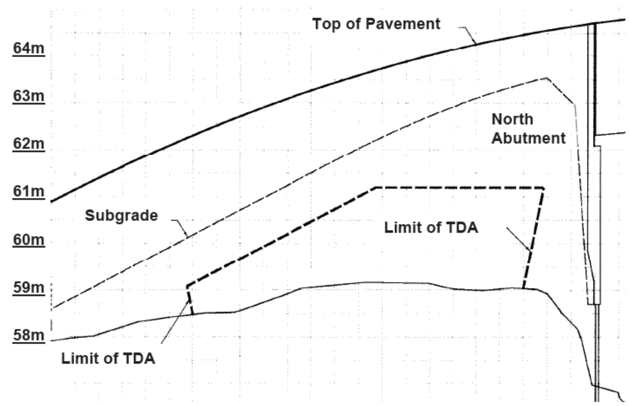

Figure 10. Longitudinal Profile – north fill (MTO 2010)

The design includes a 600 mm surcharge above ultimate profile to expedite predicted settlements within the TDA as a result of immediate compression under the weight of the overlying soil and pavement. Without the surcharge, a long term settlement of the TDA of about 30 mm was expected after final grading and paving. The Granular A surcharge is to be placed by November 25, 2011 and to remain for a minimum period of four months until March 31, 2012. Post construction settlements should be considerably less than 30 mm as a result of this surcharge. Notwithstanding, the top of the TDA layer is to be overbuilt by an amount equal to 6% of the TDA layer thickness or up to 0.2 m.

3.6 Construction

The TDA embankment is to be founded on a properly prepared foundation and consequently any softened, loosened or deleterious material is to be removed. The geotextile (OPSS 1860, Class II) that will encapsulate the TDA is then placed. TDA fill is to be spread in lifts of a maximum 300 mm thickness. Each layer of TDA is to be placed over the full width of the section. The TDA is to be spread with any equipment deemed suitable by the contractor. Each lift of TDA is to be compacted by a minimum of six complete coverage passes using vibratory smooth drum steel roller compaction equipment imposing a minimum static weight of 10 tonnes.

A special provision in the contract documents (MTO 2010) specifies the requirements for the supply, stockpiling, placement and compaction of TDA and associated works, including the supply and placement of geotextile that encapsulates the TDA and the supply and installation of outlet drains at toe of the TDA zone. The TDA must be procured from a scrap tire processor registered with OTS. TDA material specifications:

- Must be free of contaminants and foreign matter, including oil, grease, gasoline, diesel fuel, wood fragments, leaves, roots and other fibrous organic matter in order to prevent leaching into the groundwater and creation of a fire hazard.
- Must not contain remains of tires that have been subjected to a fire.
- Must have < 1% (by weight) of metal fragments that are not at least partially encased in rubber.
- Metal fragments that are partially encased in rubber must not protrude more than 25 mm from the cut edge of the TDA on 75% of the pieces (by weight) and no more than 50 mm on 90% of the pieces (by weight).
- Type B gradation specifies minimum of 90% (by weight) with a maximum dimension of 300 mm and 100% with a maximum dimension of 450 mm:
    - 75-100% passing the 203 mm sieve.
    - 0-50% passing the 76 mm sieve.
    - 0-25% passing the 37.5 mm sieve.
    - 0-1% passing the 4.75 mm sieve.

3.7 Schedule

MTO Contract No. 2010-4003 was awarded to AECON in October 2010. Design-construction handover and pre-construction meetings with the Contractor and Contract Administrator occurred in fall 2010. Construction at the Boundary Road site commenced in late 2010, including site preparation for TDA construction and installation of groundwater monitoring wells and surface water monitoring stations for baseline groundwater and surface water quality monitoring. TDA embankment construction at the project site is scheduled for mid-2011.

3.8 Material Supply

The Contractor must supply TDA in sufficient quantity and quality from a scrap tire processor registered with OTS. As of June 2011, there are 27 Registered Processors of scrap tires with OTS. The majority are located in southern Ontario, including the Moose Creek Tire Recycling Facility in south eastern Ontario. This facility is approved by MOE with a waste site processing C of A and located within 50 km from the Boundary Road project site. This close proximity to TDA supply will reduce impacts on the natural environment from truck traffic. The Contractor may also procure TDA from other OTS registered processors.

3.9 Monitoring

Engineering and environmental monitoring will be conducted for this TDA project during and following construction to confirm acceptable engineering performance and protection of the natural environment. The monitoring program includes measurement of TDA settlements, TDA internal temperature, TDA leachate quality, groundwater quality and surface water quality. Instruments strategically located within, around and below the TDA (see Figures 11 to 16) include:

- Settlement plates/rods to monitor vertical displacement and compression of TDA with time;
- Temperature cells for monitoring TDA internal temperature;
- Pan lysimeters for TDA leachate and non-TDA fill leachate;
- Groundwater monitoring wells; and
- Surface water monitoring stations.

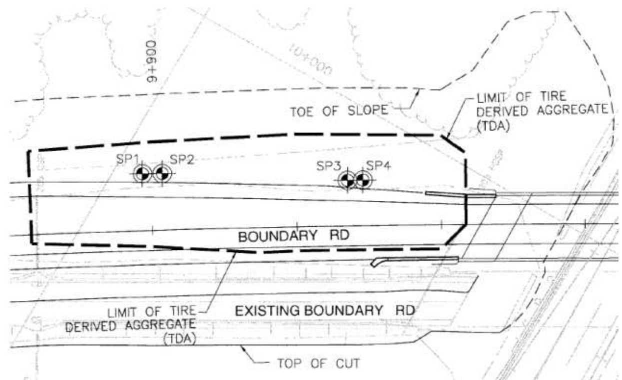

Figure 11. Settlement Plates - north fill (MTO 2010)

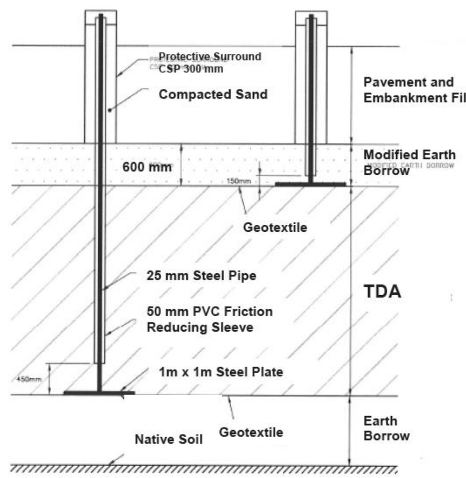

Figure 12. Settlement Plates/Rods Detail (MTO 2010)

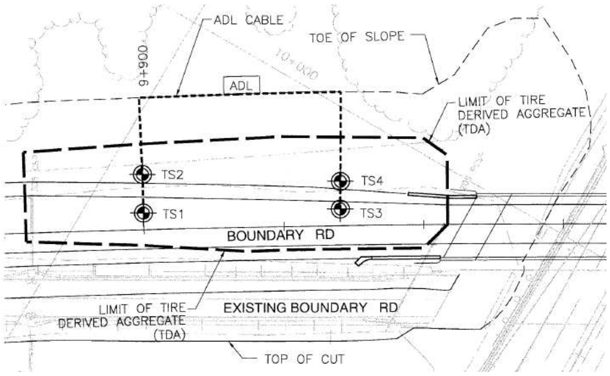

Figure 13. Temperature Sensors - north fill (MTO 2010)

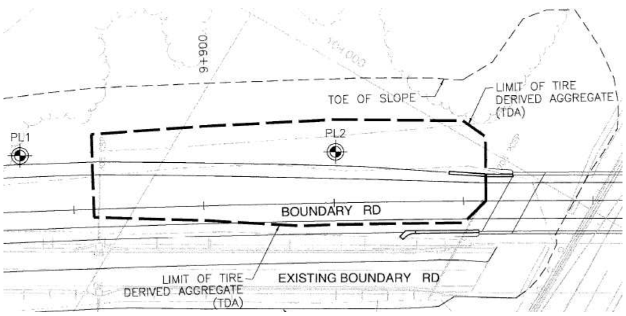

Figure 14. Pan Lysimeters - north fill (MTO 2010)

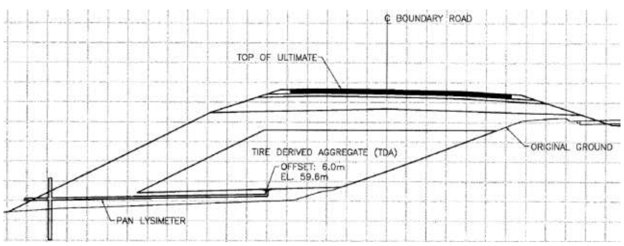

Figure 15. Pan Lysimeter Section (MTO 2010)

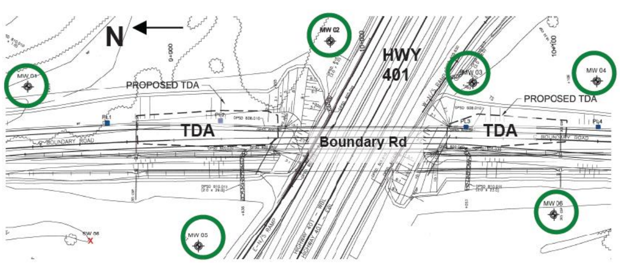

Figure 16. Groundwater Monitoring Wells (MTO 2010)

The groundwater and surface water monitoring program for this site was prepared by Coffey Geotechnics Inc. and approved by MOE. The purpose of the program is to trace the possibility of TDA leachate migration in the local groundwater and surface water systems. Six groundwater monitoring wells were installed at the site in November 2010 and pre-construction baseline water quality monitoring was completed in spring 2011. Pre-construction groundwater and surface water conditions have been established based on the results of three sets of water quality sampling and field observations.

Water quality will be monitored during and following TDA embankment construction to confirm negligible off-site effect on water quality. The program includes sampling of TDA leachate from pan lysimeters for comparison to water quality from the surrounding groundwater monitoring wells and surface water monitoring stations.

Engineering and environmental monitoring results will be reported in a future technical paper. As noted above in Section 2.4, TDA is expected to have a negligible effect on off-site water quality.

3.10 Costs

The TDA item in the MTO contract included the supply, stockpiling, placement and compaction of TDA and associated works, including the supply and placement of geotextile that encapsulates the TDA and the supply and installation of outlet drains at the toe of the TDA zone. The total cost for 3,043 tonnes of TDA is approximately $168,500 which is equivalent to about $55 per tonne.

The cost for the supply, placement, and compaction for modified earth borrow for use as soil cover for the TDA is approximately $251,000. The cost of this item, administered as a lump sum, exceeds the cost of the TDA item.

The supply and installation of the instrumentation monitoring equipment, including the settlement plates, temperature sensors, pan lysimeters, also administered as a lump sum item, is $80,700. Combining this cost with the cost of the monitoring wells at about $50,000, the total cost of the lump sum item for the supply and installation of the instrumentation is approximately $130,700.

CONCLUSIONS

The MTO proposes to use TDA as a recycled engineered material to construct highway embankments at selected locations in Ontario. Experienced gained at the Boundary Road / Highway 401 demonstration project site will be used to support future use of TDA at other sites in Ontario for highway construction, including embankment fill and backfill for retaining walls and bridge abutments.

MTO will continue to liaise with the MOE, OTS, rubber recycling industry, geotechnical community and other stakeholders to encourage the use of TDA for highway construction and other related civil engineering applications in an environmentally acceptable manner.

ACKNOWLEDGEMENTS

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REFERENCES

ASTM 2008. Standard Practice for Use of Scrap Tires in Civil Engineering Applications, D6270-08, *ASTM International (American Society for Testing and Materials)*, West Conshohocken, PA, U.S.A.

Coffey Geotechnics Inc. 2009. Foundation Investigation Report, Highway 401 / Boundary Road Bridge, City of Cornwall, Ontario, W.P. #385-01-01, Site #31-215, Geocres No. 31G-230, May 25, 2009.

Humphrey, D. N. 2005. Tire Derived Aggregate as Lightweight Fill for Embankment Construction over Soft Ground, *2005 BSCES-Geo-Institute Recent Advances in Geotechnical Engineering Seminar*, Boston, MA, U.S.A.

Humphrey, D. N. and Swett, M. 2006. Literature Review of the Water Quality Effects of Tire Derived Aggregate and Rubber Modified Asphalt Pavement, prepared for *U.S. Environmental Protection Agency Resource Conservation Challenge*, November 29, 2006.

Humphrey, D. N. 2009. Highway Applications of Tire Derived Aggregate, presented to Ontario Ministry of Transportation, October 5, 2009, Downsview, ON, Canada.

Humphrey, D. N. 2010. Foundation Investigation and Design Report for Use of Tire Derived Aggregate for Highway 401 / Boundary Road Bridge, City of Cornwall, Ontario, W.P. #385-01-01, Site #31-215, Geocres #31G-236, June 26, 2010.

Mills, B. and McGinn, J. 2008. Recycled Tires as Lightweight Fill. *Transportation Association of Canada, Annual Conference Proceedings*, Toronto, ON, Canada.

Mills, B. and McGinn, J. 2010. Design, Construction and Performance of a Highway Embankment Failure Repaired with Tire-Derived Aggregate, *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2170*, Transportation Research Board of the National Academies, Washington, D. C., 90-99.

Ontario Ministry of the Environment (MOE) 2009. Recycling Ontario’s Used Tires. www.ene.gov.on.ca.

Ontario Ministry of Transportation (MTO) 2010. Eastern Region Contract No. 2010-4003.

Wartman, J., Natale, M. F. and Strenk, P. M. 2007. Immediate and Time-Dependent Compression of Tire Derived Aggregate, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 133(3): 245-256.