Assessment of Ecological Materials as Alternative Abrasives and Deicers for Winter Road Maintenance and Water Resource Protection

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Dedication

For my family and dear friends. Their constant love and support made my graduate journey possible.

Abstract

The use of chloride-based salt as a deicer for winter road maintenance has been a longstanding practice throughout the state of Minnesota and the country. However, once chloride enters the water, it is not naturally broken down, transformed, or removed from the environment, resulting in accumulation in the watershed and detrimental ecological and water quality impacts in freshwater systems. In order to protect freshwater resources and to prevent this issue from worsening with time, an alternative method for providing sustainable and effective winter road maintenance is needed. In some cold regions of Minnesota, sand is mixed with salt as an abrasive to provide additional traction to the roads, however its effectiveness is not well established. This study aimed to investigate the potential of regionally available organic and inorganic industrial byproducts as alternatives to conventional sand and salts. Candidate materials include corn grit, timber waste, and taconite waste rocks local to Minnesota. Chemical and physical properties of the materials were characterized, including material elemental composition, morphology, particle size distribution, sorption capacity, and specific gravity to establish a foundational understanding of the material. Skid resistance tests and environmental impact assessments were performed to evaluate traction effectiveness and material safety. Based on these results, a recommendation for potential use was made. The results showed potential for corn grit to be used as a sorbent for salt brine deicer with less salt impact and for waste rock to be used as an abrasive in the realm of winter road maintenance. This work may provide potential new material for winter road maintenance as well as a streamlined method for evaluating potential abrasives/deicers, valuable for expediting future studies of alternative materials.

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List of Abbreviations

Abbreviation	**Meaning**
WRM	Winter road maintenance
MPCA	Minnesota Pollution Control Agency
TMDL	Total Maximum Daily Load
DOT	Department of Transportation
VOC	Volatile organic compound

1. Introduction

1.1 Project motivation

The use of deicers for winter road maintenance (WRM) is essential to keeping roads safe and navigable in the wintertime. However, conventional road salts (commonly chloride-based salts; NaCl, $CaCl_2$, and $MgCl_2$) cause negative environmental consequences, including corrosiveness to steel, the elevation of chloride levels in nearby water bodies, and the breakdown of soil (Evans & Frick, 2001; Fay & Shi, 2012; Ramakrishna & Viraraghavan, 2005; Stefan et al., 2008). In particular, road salt is one of major contributors to elevated chloride levels in Minnesota watersheds and the use of chloride-based salts has been an increasing trend (Sander et al. 2007). Once chloride is in water, its removal is difficult and costly, resulting in the accumulation in the watershed and increased ecological impacts (Evans & Frick, 2001). According to the Minnesota Pollution Control Agency's (MPCA) 2018 Inventory of Impaired Waters, there are 50 water bodies in Minnesota that are impaired due to chloride (MPCA, 2018). Many other water bodies have chloride levels that are steadily rising and will become impaired if concentrations continue to increase at the current rate. Moreover, a significant number of wells in the state have been found to exceed the federal chronic chloride standard of 230 mg/L (MPCA, 2018).

With sustained road salt usage, the accumulation of salts will continue to increase which will in turn exacerbate their impact. In Minnesota, the state put collaborative efforts to reduce the amount of chloride entering the environment while still providing safe winter driving road conditions. The MPCA has developed a performance-based adaptive implementation plan including water quality assessment, source identification, implementation activities, and monitoring/tracking (MPCA, 2016). As part of the implementation plan, a Total Maximum Daily Load (TMDL) of chloride has been developed for impaired waterbodies. The efforts include exploration and evaluation of alternative deicing chemicals, improved operation practices (e.g., prewetting, calibrated equipment, highway deicing standards), and implementing new technologies (e.g., ground speed control, road temperature sensors). To alleviate the growing chloride problem in Minnesota waters, it is vital to find alternative ways to meet TMDL chloride goals and protect water bodies that are not yet impaired. Thus, to protect freshwater resources and prevent this issue from worsening, an alternative method for providing sustainable and effective WRM is needed.

Along with road salt, Department of Transportations (DOT) use abrasives, commonly sand, on snow or ice-covered pavement to provide supplemental friction to roadways, especially at low temperatures when salt is not as effective. Sand abrasives are relatively inexpensive and available in large quantities. However, the use of sand within the realm of winter maintenance is considered less effective than anti-icing and de-icing methods and declining in use (Du et al., 2022). In comparison to salts, the sand applied to roads can be recovered and intercepted from reaching nearby water bodies by several practices such as sweeping, storm drain grit chambers, and holding ponds. However, when sand reaches surface water in large quantities during spring snowmelt season, it can cause turbidity increases, which is detrimental to aquatic life such as altered bottom habitats and spawning grounds (Staples et al., 2014). Additionally, sand may also bounce off the roadway especially when used on higher volume and speed roads as its effectiveness decreases as more cars travel by (Du et al., 2022; Eck et al., 1986; Guthrie, W. S., & Thomas, 2014). Unlike deicing chemicals, sand's impact on groundwater contamination is minimal (EPA, 2005)

Due to the severity of Minnesota winter, around 50,000 tons of sands have been used annually on average for the past 5 years (Minnesota Department of Transportation, 2020). The application of sands is more common in rural roads and northern Minnesota than in metro areas (Sander et al., 2008). In metro areas, the use of conventional sands has been declining to road salt only application due to the recognition of their limited effectiveness in sand/salt mixtures and street sweeping. However, the use of sands is significant for winter road operations in northern Minnesota and rural road application. In northern Minnesota, the sand is applied to icy pavement in sub-zero temperature with pre-wetting and sweeping practice and sand intercepting infrastructure such as storm drain grit chamber, and holding ponds are already in place and plan to be installed in St. Louis County, Minnesota (MPCA, 2016). Moreover, there is growing interest on alternative abrasive materials which are locally sourced and more effective than conventional sand (Hill, 2017)

In recent years, ecological materials such as wood chips and volcanic materials have been proposed as alternatives to sand and eventually road salts. In Switzerland, flat parallelepiped wood chips soaked in a brine (Stop Gliss Bio® and Eco Ice Grip) have been developed for the snow and ice-covered roads. They have been shown to provide long-lasting traction and deicing performance in low traffic road below sub-zero temperature (Mucaria, 2018). There have been similar pilot-scale practices and field tests to use wood chips in other cities (e.g. Quebec, Canada and Denver, Co). Locally sourced minerals can be another option. Likewise, natural volcanic minerals and zeolite may provide better traction over sand and dark color offer ice melting through insolation (EcoTraction TM; Nieves et al., 2017; Wenta & Sorsa, 2016). In Minnesota, there are natural materials such as woodchips, corncob grits, and iron-bearing minerals which may be better alternatives to sand. Thus, it is worthy to explore locally sourced green materials which may have feasibility and effectiveness as alternative abrasives.

1.2 Project overview/goals/objectives

This study investigated the performance and environmental impact of a variety of organic and inorganic industrial byproducts local to Minnesota as potential alternatives to conventional sand and salts. The implementation of a better performance road abrasive may help decrease road salt application usage while still providing safe roads. The benefit of selecting locally sourced material may be lower transportation costs and providing a beneficial use for otherwise waste product. The materials used in the analyses were corn grit, timber waste, and taconite waste rocks. Analyses were performed on the raw materials and brine infused versions of the materials. An environmental impact and performance evaluation was conducted to provide a baseline assessment of potential implications associated with their application. After completing individual material testing, a final recommendation was made regarding WRM application use. An overview of the general project structure can be found below in Figure 1.

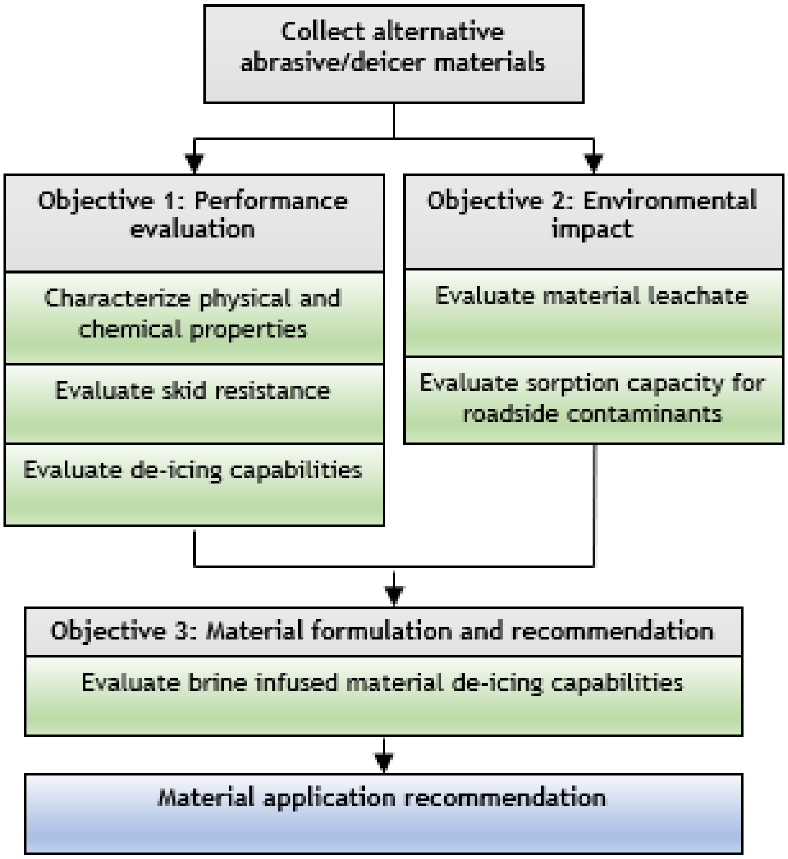


Figure 1. Flowchart summarizing project structure. The project goal is to evaluate alternative winter maintenance materials for use.

The overarching goal of the study was to investigate the potential of a variety of organic and inorganic industrial byproducts such as corn grit, timber waste, and taconite waste rocks local to Minnesota as alternatives to conventional sand and salts for WRM. Specific objectives and hypotheses were:

Objective 1: Evaluate abrasive and deicing performance of the candidate materials through material particle-size distribution, specific gravity, bulk density, angularity, morphology, skid resistance, and deicing capacity.

Hypothesis 1: *The inorganic materials such as waste rocks will have potential to be used as abrasives because of their observed hardness/morphology while organic materials will have effective deicing potential when combined with salt brine because of their predicted higher porosity and sorption capacity.*

Objective 2: Investigate environmental impacts of the selected materials with acceptable abrasive and deicing performance upon their use on road through chemical composition, leachate analysis, and sorption capacity.

Hypothesis 2: *The organic project materials will have a larger environmental impact in comparison to inorganic project materials because of their inherent ability to leach nutrients, deplete oxygen, and increase turbidity, amongst other factors.*

Objective 3: Formulate and recommend a mixture of the raw materials that can potentially be used during WRM based on the findings from objectives 1 and 2.

Hypothesis 3: *Inorganic waste rock material may replace or outperform sand as an abrasive and brine-soaked organic material can be alternative as a slow-release deicer.*

2. Materials and Methodology

2.1 Material selection

Readily available byproduct materials were assessed for potential abrasive use. These materials were sourced from local Minnesotan industries and consisted of mulches, corn grits, and mining waste rocks. Reference materials were evaluated alongside for comparison purposes and consisted of conventional sand and rock salt as well as a traction salt-free alternative consumer product material. Materials are identified and pictured in Figure 2. The two waste rock samples are differentiated as OX and MES for clarity.

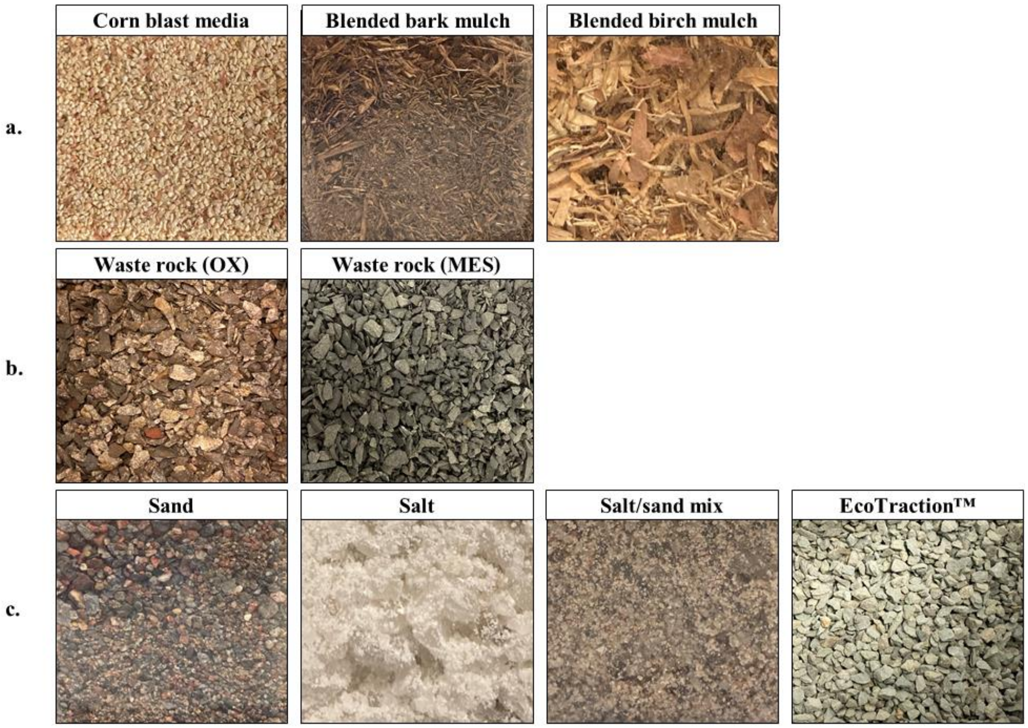


Figure 2. Project material used for evaluation. Local alternative abrasive materials were (a) mulches and corn grits as organic material and (b) mining waste rocks as inorganic materials. (c) Conventional materials and a traction salt-free alternative consumer product material were used for comparison.

2.2 Performance Evaluation

2.2.1 Physical properties

The particle-size distributions for non-reference materials were determined through sieve analysis in accordance with the *ASTM C 136-06: Standard Test*

Method for Sieve Analysis of Fine and Coarse Aggregates standard protocol and performed in duplicates (ASTM, 2006). Samples of 500 grams were oven-dried overnight at a 110°C prior to sieving and were re-weighed once cooled. Standard sieves numbered 3/8”, 4, 8, 16, 30, 50, 100, and 200 were used with a mechanical sieve shaker to sieve the material. Mass retained was measured with a balance to the nearest tenth of a gram for percent passing calculations and for creating gradation plots. Values for sieved materials’ fineness modulus and coefficient of uniformity (C_u) were also calculated from these results to represent the materials’ average particle-size index and gradation uniformity, respectively. Following particle-size characterization, material stocks were standardized within the recommended particle-size range for anti-skid materials in WRM referenced in the EPA guidance and MnDOT district 1 sand size distribution to be larger than 297 µm (ASTM Sieve No. 50) and smaller than 4.75 mm (ASTM Sieve No. 4), by removing material above or below this spec range. The range purpose is to remove any silt content to prevent dust/PM_{10} pollution and to remove larger particles to prevent damage to equipment and vehicles (U.S. EPA, 1990).

Specific gravity tests were performed by pycnometer/gravimetric method in accordance with the *ASTM C-128: Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate* standard protocol (ASTM, 2015). Samples of 500 grams were oven-dried overnight at a 110°C prior to testing. After drying, the samples were soaked in water for a 24-hour period, drained, and mechanically dried until saturated-surface-dry conditions were achieved. The prepared sample was poured into the pycnometer vessel, filled with water, mixed, and weighed. The samples were then oven-dried again at 110°C for dry weight measurements. Test results were used to calculate bulk specific gravity (oven-dry condition), specific gravity (saturated-surface-dry condition), apparent specific gravity, and water absorption. Only one replicate was needed for representative data.

Bulk density tests were performed by “shoveling” method in accordance with the *ASTM C-29/29M: Standard Test Method for Bulk Density (“ Unit Weight ”) and Voids in Aggregate* standard protocol (ASTM, 2009). A 50 mL graduated cylinder was used as the measurement vessel and was cleaned, dried, and weighed before material addition. Material stockpiles were well-mixed prior to measurement and samples were scooped from stockpiles and poured directly into the measurement cylinder. The cylinder was filled until material additions reached the 50 mL calibrated capacity in which the final volume was weighed on a balance to the nearest ten-thousandth of a gram. Material stocks were well-mixed prior to measurement to ensure a representative sample. Test results were used to calculate the uncompacted/loose bulk density of the materials. Only one replicate was required.

Material morphological observations, including angularity, were assessed via imaging using a Hitachi TM3030Plus Tabletop Scanning Electron Microscope (SEM). Material stockpiles were well-mixed prior to scooping to ensure a representative sample and conductive copper SEM tape was used to adhere the sample to the imaging mount. SEM imaging settings were set to a voltage of 5 kV for clear imaging of surface structure, an electron detection of secondary electrons (SE) for topographic imaging purposes, and high magnification mode for image clarity/quality. The working distance was maintained at approximately 8 mm. Images were taken at magnifications of x100, x1000, and x2500 for each of the four quadrants of the mounted sample to obtain group and individual particle images. After imaging, material angularity was determined using the obtained images and the Powers scale classification system shown in Figure S1 of the supplementary material section to classify angularity, sphericity, and resulting roundness indices (Chu et al., 2009).

2.2.2 Chemical properties

Materials were digested to analyze elemental composition using Aqua Regia digestion methodology adapted from *U.S. EPA Method 3050B: Acid Digestion of Sediments, Sludges, and Soils* (U.S. EPA, 1996). Digestions were performed in duplicate, and glassware was acid washed to remove potential contamination. For the digestions, a 0.1-gram sample was taken from well-mixed material stockpiles and combined with 10 mL of reagent grade hydrochloric acid and 2.5 mL of reagent grade nitric acid in a 250 Erlenmeyer flask digestion vessel. The vessels were covered with a ribbed watch glass and refluxed at 95°C ± 5°C using a hot plate for 30 minutes. After 30 minutes, 5 mL of reagent grade hydrogen peroxide was added to ensure reaction completion. After effervescence from the peroxide addition subsided, the vessels were removed from heat and cooled to room temperature, 20°C. Once cooled, the digestate was filtered through a Whatman No. 41 filter using vacuum filtration and diluted to 100 mL in a volumetric flask with 0.5% nitric acid. Samples were preserved in the freezer at -20°C until analysis. Samples were sent to the St. Paul Research Analytical Laboratory within the University of Minnesota College of Food, Agricultural and Natural Resource Sciences for Inductively Coupled Argon Plasma Optical Emission Spectrometer (ICP-OES) elemental analysis. Twenty-seven elements were measured, including heavy metals arsenic, cadmium, chromium, copper, nickel, and lead. Material elemental concentrations were converted from mg contaminant/L material digestate to mg contaminant/g solid material.

2.2.3 Friction measurement

To our knowledge, there is no standard method to evaluate skid resistance of abrasives (loose materials) on pavement surface. A Pendulum Skid Tester (Gilson HM-602W Pendulum Skid Tester) was chosen as the abrasive friction measurement tool because of its transportability and accessibility, which was better suited to conduct a controlled, lab-scale study that is within the research scope. Tests were first performed in lab using a bare ice sheet (Figure S3) as the test surface but were stopped because of quality control issues with temperature melting the ice prematurely and reproducibility of the ice surface. Field tests were attempted by creating an icy road surface but were stopped because of difficulties with creating the ice layer as the water would seep through the pavement before freezing. A snow layer was attempted (Figure S4) to use but was stopped because of high standard deviations between replicates making it difficult to draw conclusions. In future applications, field testing may be pursued using a larger-scale method like paired car/wheel hitch device (Fay & Shi, 2011).

The test method was adapted with modification from the *ASTM E303: Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester* standard protocol (ASTM, 2014). A Gilson 3in Mounted Slider (model HMA-203) was used as the pendulum slider to model a standard rubber automotive tire and was conditioned prior to use. Concrete and asphalt road surfaces can be seen in Appendix A Figure S2. All tests were performed at room temperature, 20°C, and each material was applied to the test surface at an application rate of 1390 lbs/lane-mile (personal communication with Minnesota Department of Transportation professionals). Prior to testing, the pendulum was calibrated by zeroing, leveling, and slide length adjustment. The test surface was thoroughly cleaned with a soft-bristle brush, material was applied at random across the test area, and a 2.25 kg metal roller was rolled across the test surface 5 times to wear the material in the test surface. The background friction was measured between tests to characterize the test surface and verify consistent surface roughness through testing. The pendulum arm was then released, and skid resistance was quantified with the resulting British pendulum number. To lower test variability, four replicates were done per test, the test material was re-scattered as a fresh application onto a clean test surface for each replicate, and the slide length was checked between tests. Pavement types and background friction values are included in the appendix for reference (Figure S2).

2.2.4 Deice capacity

Deicing performance was evaluated using a modified version of the *SHRP H-205.1: Deicing Performance Ice Melting Test* (Chappelow et al., 1992). Corning® Costar® polystyrene 6-well plates (2 rows of 3 wells, 3.48 cm well diameter, 9.5 cm^2 well area) were used to create 0.5 cm thick ice sheets by freezing 5 mL of deionized water per well. The ice sheets were frozen, partially melted with a handheld blower, and then refrozen to create a smooth and level test surface. Ice sheets were equilibrated at test temperature, 4°C,for 24 hours prior to testing. The test temperature in a testing chamber was regulated with an external temperature control system (InkBird ITC-308), ice packs, and insulated containers for the well plates (Lavex Insulated Box Liners). Material additions were standardized to MnDOT's current application rates. Ice melt volume was collected at the proposed time intervals of 1, 5, 7 hours. Sampling involved measuring the ice melt volume and taking a thermal image. Ice melt was mixed and re-equilibrated to test temperature for 15 minutes before returning the well-plate. Additionally, the conductivity of the final ice melt was measured to estimate chloride content in the melt. Experiments were performed in triplicate.

2.3 Environmental impact

2.3.1 Sorption capacity

Sorption isotherm experiments were conducted to evaluate the materials' sorptive removal potential for common roadside contaminants. Road contaminants lead, copper, benzene, and chloride were selected as a heavy metal, volatile organic compound (VOC), and road salt contaminant, respectively. Solutions were created at a solid to liquid ratio of 13:1 to evaluate a fixed mass over a range of contaminant concentrations. Test solutions were covered with aluminum foil to prevent any potential photolysis reactions and then mixed to equilibrium at room temperature, 20°C, for 3 days using a Lab-Line 3520 Orbital Shaker at a constant speed of 350 rpm. After equilibration, test solutions were either filtered with a 0.22 µm PTFE filter for benzene and with a nylon filter for all other samples and stored in the fridge at 4°C until analysis. Glass vials, pipettes, and syringes were used for VOC sample handling and plastic materials were used for the handling of all other samples. Tests were performed in triplicate and chemicals were reagent grade.

A ~10,000 mg/L benzene stock solution was created in methanol and used to make test solution concentrations ranging from approximately 1-11 mg/L benzene mixed in a Milli-Q® water matrix (Shi et al., 2020). To avoid benzene loss via volatilization, solutions with minimal headspace were sealed with PTFE coated septa and aluminum crimps. Concentrations were determined using a High-Pressure Liquid Chromatography with UV Detector (HPLC-UV) equipped with a C18 column and 30-70 water-methanol mobile phase at 254 nm wavelength (Bahrami et al., 2011). Data was extracted with CHROMELEON® 7 software.

A 2 M NaCl stock solution was created in Milli-Q® water and used to make test solution concentrations ranging from approximately 1-10 mg/L chloride mixed in a Milli-Q® water matrix (Robinson et al., 2017). Concentrations were determined using a Thermo Scientific™ Ion Chromatography Instrument, a standard curve was created with Thermo Scientific™ Dionex™ Ion Standards stock solution, and data was extracted with CHROMELEON® 7 software. Samples were cation filtered prior to analysis.

A 100 mg/L copper (I) chloride stock solution was created in Milli-Q® water with 1.2% HNO_3 (V/V) and used to make test solution concentrations ranging from approximately 1-3.5 mg/L copper mixed in the acidified Milli-Q® water (Walaszek et al., 2018). Similarly, a 1000 mg/L lead (II) nitrate stock solution was created in Milli-Q® water with 1.2% HNO_3 (V/V) and used to make test solution concentrations ranging from approximately 1-15 mg/L lead mixed in the acidified Milli-Q® water (Walaszek et al., 2018). Equilibrated metal concentrations were determined using flame atomic absorption spectrometry (F-AAS) Varian AA240FS and Agilent SpectrAA Software (APHA et al., 2017).

2.3.2 Leaching potential

A batch leaching study was conducted to identify potential water quality concerns that could result from future application of the materials on the roadway. The *Leaching Environmental Assessment Framework (LEAF)* was used as a guide in the experimental design (Kosson et al., 2017). A 20:1 liquid to solid ratio was used to create material leaching solutions in 250mL Nalgene® High-Density Polyethylene Bottles. A balance and volumetric flask were used to measure out 7.5 g of material and 150 mL of Milli-Q® water, respectively. The solutions were agitated using a Lab-Line 3527 Bench Top Orbit Environ Shaker Incubator at a constant speed of 100 rpm and temperature of 33±1°C. Leaching times were evaluated for 1-day, 2-days, 1-week, and 3-weeks. Material leaching solutions were performed in triplicate and were remade for each time interval. Samples were analyzed for direct measurements (temperature, pH, conductivity, dissolved oxygen), alkalinity, turbidity, total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), select anions, and select cations. All samples, except anions, were removed of large particles with a clean 70 µm mesh filter prior to collection. Anion samples were filtered with a 0.22 µm filter using vacuum filtration prior to sample storage and were cation filtered prior to analysis. TOC samples were stored in amber vials and all other samples were stored in polypropylene centrifuge tubes. TP/TN and cation samples were stored in the freezer at -20°C and all other samples were stored in the fridge at 4°C until analysis. TOC, cation, and TP/TN samples were acidified.

Direct measurements were taken immediately upon sampling with calibrated benchtop probes. Measurements were taken the next day for turbidity with a Hach 2100P ISO Portable Turbidimeter and alkalinity with standard titration method (APHA et al., 2017). Anion analysis was performed using a Thermo Scientific™ Ion Chromatography Instrument, a standard curve was created with Thermo Scientific™ Dionex™ Ion Standards stock solution, and data was extracted with CHROMELEON® 7 software. Cation and TOC samples were sent to the St. Paul Research Analytical Laboratory within the University of Minnesota College of Food, Agricultural and Natural Resource Sciences for analysis. Cation samples were analyzed using ICP-OES for 27-cations, including heavy metals arsenic, cadmium, chromium, copper, nickel, and lead and TOC samples were analyzed using a Phoenix-Dohrmann 800 TIC/TOC Analyzer. TP/TN samples were measured using Hach® Test ‘N Tube™ kits, DRB200 Digital Reactor Block, and DR 1900 Spectrophotometer and accompanied methodology (Hach Company, 2015b, 2015a).

2.4 Material formulation

2.4.1 Brine infused material

Brine infused versions of the materials were created using conventional salt brine and method guidance from *ASTM D2216: Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass* (ASTM, 1998). Conventional salt brine used for the infusion was created by mixing reagent grade NaCl in Milli-Q® to make a 23.3% NaCl brine solution. Twenty grams of each material were placed in oven safe glass jars and saturated with brine solution. Brine solution volumes added to saturate the materials were 100 mL for organic materials and 50 mL for all other materials and were measured using a volumetric flask. The jars were sealed, and the materials were left to soak at room temperature, 20°C, for 3 days. After 3 days, the remaining liquid brine was drained from the sample jar and stored in PP centrifuge tubes in the 4°C fridge where they were later measured for conductivity using a benchtop probe. The soaked materials were oven dried at 110±5°C for 24 hours and cooled. Mass measurements were taken at each stage to create a mass balance for the infusion that may be used to assess material brine holding capacity and to derive the salt dosage of the newly infused material.

2.4.2 Evaluation

The infused materials were tested against conventional deicers, salt and salt/sand mixture, for deicer performance. Salt dosage was derived from the mass balance recorded during formulation and application rates were standardized to MnDOT’s current application rates. Deicer methods were the same as summarized in section 2.2.4.

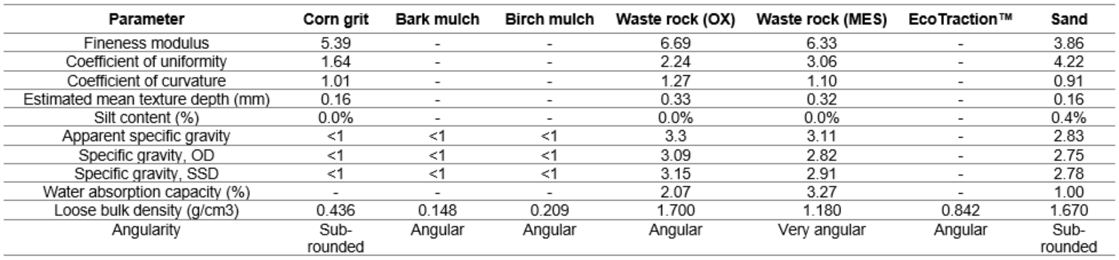
3. Results and Discussion

3.1 Performance evaluation

3.1.1 Physical properties

Material physical property characterization results can be found in Table 1 below.

Table 1. Compiled physical properties of project material used to assess potential for winter maintenance application.



Parameter	Corn grit	Bark mulch	Birch mulch	Waste rock (OX)	Waste rock (MES)	EcoTraction™	Sand
Fineness modulus	5.39	-	-	6.69	6.33	-	3.86
Coefficient of uniformity	1.64	-	-	2.24	3.06	-	4.22
Coefficient of curvature	1.01	-	-	1.27	1.10	-	0.91
Estimated mean texture depth (mm)	0.16	-	-	0.33	0.32	-	0.16
Silt content (%)	0.0%	-	-	0.0%	0.0%	-	0.4%
Apparent specific gravity	<1	<1	<1	3.3	3.11	-	2.83
Specific gravity, OD	<1	<1	<1	3.09	2.82	-	2.75
Specific gravity, SSD	<1	<1	<1	3.15	2.91	-	2.78
Water absorption capacity (%)	-	-	-	2.07	3.27	-	1.00
Loose bulk density (g/cm3)	0.436	0.148	0.209	1.700	1.180	0.842	1.670
Angularity	Sub-rounded	Angular	Angular	Angular	Very angular	Angular	Sub-rounded

3.1.1.1 Particle-size distribution

The fineness moduli, coefficients of uniformity and estimated mean texture depths (EMTD) of pre-sieved materials are presented in Table 1 and the gradation curves are presented in Appendix B Figure S5. The corn grit and waste rocks were classified as coarse and the sand as fine as per ranges specified by the U.S. Army Corps of Engineers using calculated fineness modulus values (USACE, 1980). Material gradations were classified as uniform for both waste rocks and corn grit and as non-uniform for sand as per the Unified Soil Classification System using calculated coefficients of curvature (ASTM, 2006b). Silt material accounted for 0% of the unfiltered waste rocks and corn grit and 0.4% of the sand, indicating low PM_{10} pollution potential for the materials. Material retained on No.8 and 16 sieves, which has been previously studied to influence friction enhancement the most, accounted for 99.8% of corn grit, 32.6% of sand, and 99.6% and 96.3% of OX and MES waste rocks, respectively. In comparison, material passing through the No.50 sieve, which has been previously studied to have little influence on friction enhancement, accounted for 0% of corn grit, 15.5% of sand, and 0.1% of both waste rocks (U.S. EPA, 1990).

The estimated mean texture depth was found to be highest for waste rock (OX) and then waste rock (MES), corn grit, and sand, respectively, and was used to estimate potential for friction enhancement with respect to macrotexture of the materials after application (National Academies of Science Engineering and Medicine, 2009; Stroup-Gardiner & Brown, 2000). Particle-size distribution results for both mulch materials were not reported because their inherent tenderness caused breakage during sieving which consequently resulted in data not representative of the raw materials' true gradation.

Of the candidate materials, the waste rocks' coarse and uniform nature indicated the strongest potential for use as a friction enhancer in winter maintenance as influenced by gradation results. If applied, removal of any larger (>4.75 mm) particles present within the rocks' raw gradations may be recommended for removal to lower potential environmental, infrastructure, and safety hazard risks. Additionally, the corn grit had notable friction enhancement potential and would not be recommended for filtration prior to application. However, its tenderness as an organic material has a higher potential for crushability when on the roadway and would need to be thoroughly evaluated prior to potential application (U.S. EPA, 1990).

3.1.1.2 Specific gravity and bulk density

The oven-dry specific gravity, saturated-surface-dry specific gravity, apparent specific gravity, water absorption, and bulk density are presented in Table 1. Density values were highest for waste rock (OX), followed by waste rock (MES) and sand, respectively. Water absorption was largest for waste rock (MES), followed by waste rock (OX) sand, respectively. Exact specific gravity values for organic materials were not able to be determined through the test methods used because of the materials' flotation and are therefore reported generally as <1. Material bulk density ranged from 0.148-1.700 g/cm^3 and was largest for waste rock (OX), followed by sand, waste rock (MES), EcoTraction™, corn grit, birch mulch, and then bark mulch, respectively. This may potentially help lower weight of transportation but may not change storage volume as dramatically. Values may help guide various design specifications related to winter maintenance application including application rate, surface area coverage and storage volume. Bulk densities may be particularly useful in providing a form of density characterization particularly for the organic materials, which were not able to have specific gravity values determined through the test methods used. The lower bulk densities for organic materials suggest a potential for smaller mass of product needed to provide equivalent surface area coverage. This may help to lower weight of transportation and result in potentially lower associated transportation costs for the DOT but may not change storage volume as dramatically and would be dependent on the application rate needed as validated by performance.

3.1.1.3 Angularity

Material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features were characterized using SEM analysis (Exemplary SEM images of corn grit in Figure 3 and those of other materials in Appendix B Figures S6-S14). The sand and corn grit materials were characterized as sub-rounded and the remaining materials were characterized as angular, with the waste rock (MES) characterized as very angular (Table 1). Visual porosity was observed for EcoTraction™ as well as for all of the organic materials with corn grit seeming to be the most porous. Angular materials, most notably waste rock (MES), were considered to have higher potential for use as a friction enhancer attributed to the material microtexture. Although the organic materials were as angular in comparison, their observable porosity suggested better potential holding capacity for salts or roadside contaminants.

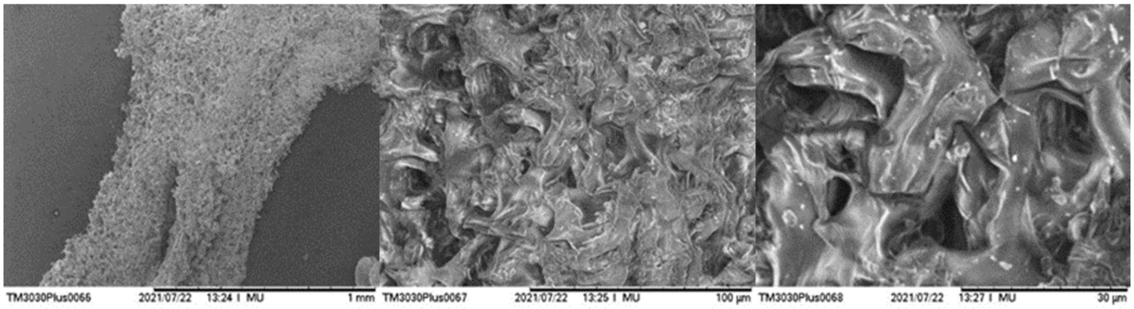
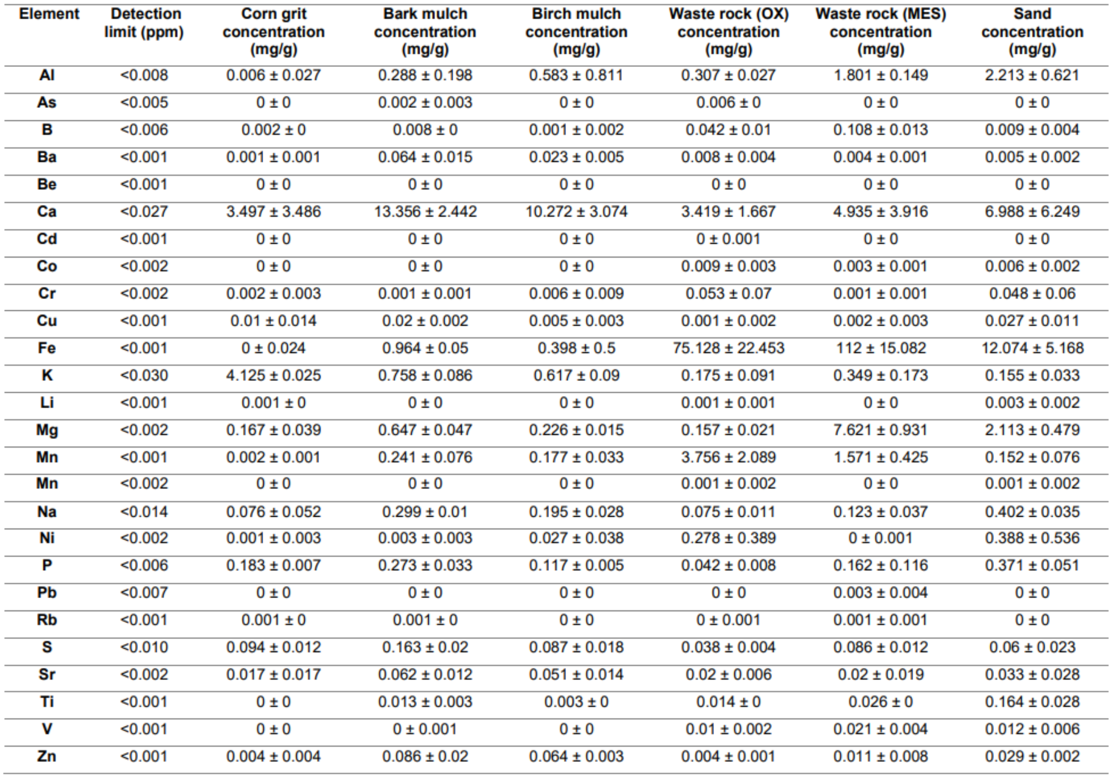


Figure 3. Exemplary scanning electron microscopy images of candidate abrasive corn grit used for the characterization of material morphological features.

3.1.2 Chemical properties

Material elemental composition was analyzed to examine whether the materials contain heavy metals and what elements could be leachable to environment upon their application to the road (Table 2). The materials were found to be primarily composed of iron, calcium, aluminum, magnesium, and silica. Generally, the organics were highest in calcium and the inorganics were highest in iron. The materials contain no or very low quantity (< 0.02%) of heavy metals (Pb, Zn, Cu, Cr etc.), indicating these materials have low pollution potential (EPA, 1995). Organic materials, corn grit and mulches were commonly composed of potassium, calcium, phosphorus, and magnesium. Corn grit contained phosphorus (0.183 mg/g) while mulch materials had more iron and aluminum in comparison to corn grit. As waste rocks (OX and MES) were byproducts of taconite process, they were rich with iron, manganese, calcium, and aluminum. The elements most highly represented in sand were iron, calcium, aluminum, and magnesium. It is noted that the amount of silica was not included as aqua regia digestion cannot dissolve silica. Elemental concentrations were received in mg/L units and were converted to mg/g units using the recorded digested material mass to represent total presence in the solid material.

Table 2. Average elemental concentrations of digested project materials (n=3) for 27 elements. Results obtained from Aqua Regia digestion (modification of EPA method 3050B) and ICP-OES analysis.



Element	**Detection limit (ppm)**	**Corn grit concentration (mg/g)**	**Bark mulch concentration (mg/g)**	**Birch mulch concentration (mg/g)**	**Waste rock (OX) concentration (mg/g)**	**Waste rock (MES) concentration (mg/g)**	**Sand concentration (mg/g)**
Al	<0.008	0.006 ± 0.027	0.288 ± 0.198	0.583 ± 0.811	0.307 ± 0.027	1.801 ± 0.149	2.213 ± 0.621
As	<0.005	0 ± 0	0.002 ± 0.003	0 ± 0	0.006 ± 0	0 ± 0	0 ± 0
B	<0.006	0.002 ± 0	0.008 ± 0	0.001 ± 0.002	0.042 ± 0.01	0.108 ± 0.013	0.009 ± 0.004
Ba	<0.001	0.001 ± 0.001	0.064 ± 0.015	0.023 ± 0.005	0.008 ± 0.004	0.004 ± 0.001	0.005 ± 0.002
Be	<0.001	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Ca	<0.027	3.497 ± 3.486	13.356 ± 2.442	10.272 ± 3.074	3.419 ± 1.667	4.935 ± 3.916	6.988 ± 6.249
Cd	<0.001	0 ± 0	0 ± 0	0 ± 0	0 ± 0.001	0 ± 0	0 ± 0
Co	<0.002	0 ± 0	0 ± 0	0 ± 0	0.009 ± 0.003	0.003 ± 0.001	0.006 ± 0.002
Cr	<0.002	0.002 ± 0.003	0.001 ± 0.001	0.006 ± 0.009	0.053 ± 0.07	0.001 ± 0.001	0.048 ± 0.06
Cu	<0.001	0.01 ± 0.014	0.02 ± 0.002	0.005 ± 0.003	0.001 ± 0.002	0.002 ± 0.003	0.027 ± 0.011
Fe	<0.001	0 ± 0.024	0.964 ± 0.05	0.398 ± 0.5	75.128 ± 22.453	112 ± 15.082	12.074 ± 5.168
K	<0.030	4.125 ± 0.025	0.758 ± 0.086	0.617 ± 0.09	0.175 ± 0.091	0.349 ± 0.173	0.155 ± 0.033
Li	<0.001	0.001 ± 0	0 ± 0	0 ± 0	0.001 ± 0.001	0 ± 0	0.003 ± 0.002
Mg	<0.002	0.167 ± 0.039	0.647 ± 0.047	0.226 ± 0.015	0.157 ± 0.021	7.621 ± 0.931	2.113 ± 0.479
Mn	<0.001	0.002 ± 0.001	0.241 ± 0.076	0.177 ± 0.033	3.756 ± 2.089	1.571 ± 0.425	0.152 ± 0.076
Mn	<0.002	0 ± 0	0 ± 0	0 ± 0	0.001 ± 0.002	0 ± 0	0.001 ± 0.002
Na	<0.014	0.076 ± 0.052	0.299 ± 0.01	0.195 ± 0.028	0.075 ± 0.011	0.123 ± 0.037	0.402 ± 0.035
Ni	<0.002	0.001 ± 0.003	0.003 ± 0.003	0.027 ± 0.038	0.278 ± 0.389	0 ± 0.001	0.388 ± 0.536
P	<0.006	0.183 ± 0.007	0.273 ± 0.033	0.117 ± 0.005	0.042 ± 0.008	0.162 ± 0.116	0.371 ± 0.051
Pb	<0.007	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0.003 ± 0.004	0 ± 0
Rb	<0.001	0.001 ± 0	0.001 ± 0	0 ± 0	0 ± 0.001	0.001 ± 0.001	0 ± 0
S	<0.010	0.094 ± 0.012	0.163 ± 0.02	0.087 ± 0.018	0.038 ± 0.004	0.086 ± 0.012	0.06 ± 0.023
Sr	<0.002	0.017 ± 0.017	0.062 ± 0.012	0.051 ± 0.014	0.02 ± 0.006	0.02 ± 0.019	0.033 ± 0.028
Ti	<0.001	0 ± 0	0.013 ± 0.003	0.003 ± 0	0.014 ± 0	0.026 ± 0	0.164 ± 0.028
V	<0.001	0 ± 0	0 ± 0.001	0 ± 0	0.01 ± 0.002	0.021 ± 0.004	0.012 ± 0.006
Zn	<0.001	0.004 ± 0.004	0.086 ± 0.02	0.064 ± 0.003	0.004 ± 0.001	0.011 ± 0.008	0.029 ± 0.002

3.1.3 Friction measurement

The friction testing in Figure 4 generally showed better performance of inorganic waste rock candidate materials compared to the organic candidate materials. Friction values of pavement types and background surface (bare ice surface) are included in the appendix for reference (Figure S2). The friction performance of the mulches was overall lower but still relatively comparative to that of the waste rocks whereas the corn grits was much lower than all other tested materials by roughly 10 BPN. Of the reference materials, EcoTraction™ performed best and was matched in performance by waste rock (MES). An arbitrary safety threshold of 50 BPN was chosen from literature recommendations and background friction values for different pavement types and was met on all surfaces for waste rock (OX), waste rock (MES), bark mulch, and EcoTraction™ and only on asphalt for salt and concrete for sand (National Academies of Science Engineering and Medicine, 2009). No observable trend was noted between pavement surface type and material friction performance, but it's suspected that present variances may be attributed to differences in pavement porosity as well as general experimental variability. Overall, the testing showed that waste rock (MES) had the strongest potential for abrasive use followed by waste rock (OX), bark mulch, and birch mulch. The potential drawbacks of mulch abrasive application, including durability attributed to material tenderness and roadway longevity attributed to its lighter nature, should also be considered.

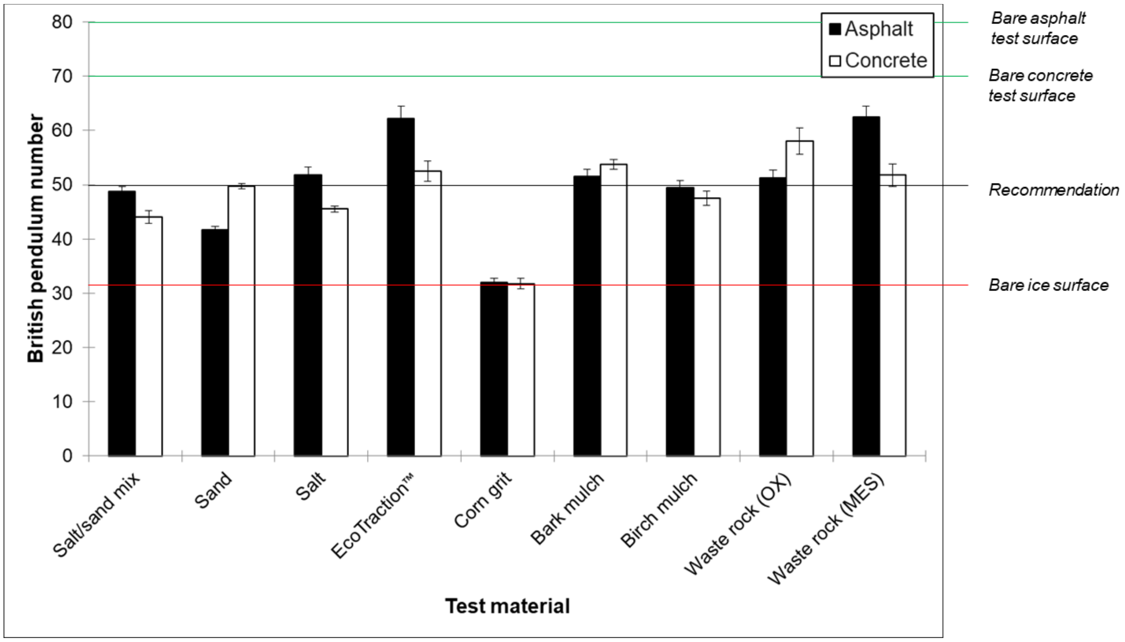


Figure 4. Project material British Pendulum Number (BPN) results from skid resistance tests. Thresholds are shown for bare pavement test surfaces (no abrasive), bare ice surface and a BPN of 50 is shown to represent an arbitrary recommended safety threshold. A margin of error equal to or less than 2 BPN was reported for all tests (n=4).

3.1.4 Deice capacity

Deicing capabilities were not observed for the raw candidate abrasive materials at the temperature and time intervals of testing which mostly aligned with experimental expectations. Because corn derivates have been shown to exhibit deice capabilities in previous studies, the candidate corn grit material was of particular interest but, as stated, did not demonstrate melt capacity in its tested condition (Abbas et al., 2021; Yellavajjala et al., 2020).

3.2 Environmental impact

3.2.1 Sorption capacity

The sorption capacity of the materials for the selected road contaminants was evaluated using a linear sorption isotherm model. Isotherms were obtained graphically by plotting the experimental results of contaminant mass sorbed per mass of material, q_e (mg/g), calculated using the equation below, as a function of the final equilibrated contaminant concentration in the test solution, C_e (mg/L) (Zuhairi, 2003).

$$q_e = \frac{(C_o - C_e) * V}{M * 1000}$$

Where:
q_e = Contaminant mass sorbed per material mass (mg/g)
C_o = Contaminant concentration in solution at the start of testing (mg/L)
C_e = Equilibrated contaminant concentration in solution at the end of testing (mg/L)
V = Test solution volume (mL)
M = Material mass (g)

Linear isotherms were used for simplification because of the narrow range of contaminant concentrations tested. Sorption coefficients, K_d (L/g), were determined graphically using the slope estimations of respective isotherms and were used to mark performance. Figure 5 contains the materials' experimental sorption capacities as K_d for the contaminants benzene and lead that had measurable sorption by the materials. It was found that the materials generally had sorption capacity for both benzene and lead. While benzene was sorbed preferably into organic materials and EcoTraction™, lead showed sorption affinity across all materials. Birch and bark mulches had greater sorption affinity for benzene and lead along with EcoTraction™. There was no observable sorption of copper or chloride by the materials at the concentrations tested.

The greater capacities of mulches and EcoTraction™ may be attributed to greater porosity, the organic content of the mulches, and the zeolite composition of EcoTraction™. The observed overall lower sorption capacity of heavy metals by all materials may partly be attributed to a lower pH of the test water matrix, which has been observed to negatively influence sorption (Walaszek et al., 2018). Acidified matrices were only used for heavy metal contaminants in order to increase dissolution and pH was not monitored for any of the tests so its influence can only be speculated. Further research is suggested to study the nature and extent of the materials' sorption capacity beyond this preliminary study, potentially utilizing a more expansive dataset of sorbent/sorbate concentration, pH, time, and temperature. The graphs used to derive K_d and table containing K_d values and respective coefficients of determination, R^2, are included in Appendix B (Figure S14 and Table S2). The assumption of a linear isotherm model fit for the observed sorption patterns with R^2 values ranging from 0.760-0.984 for K_d at test conditions. Potential sources of error pertaining to all materials may be with material particle variability, i.e. size, shape, texture. Lack of particle uniformity may result in varying sorption capacity properties and consequent experimental results.

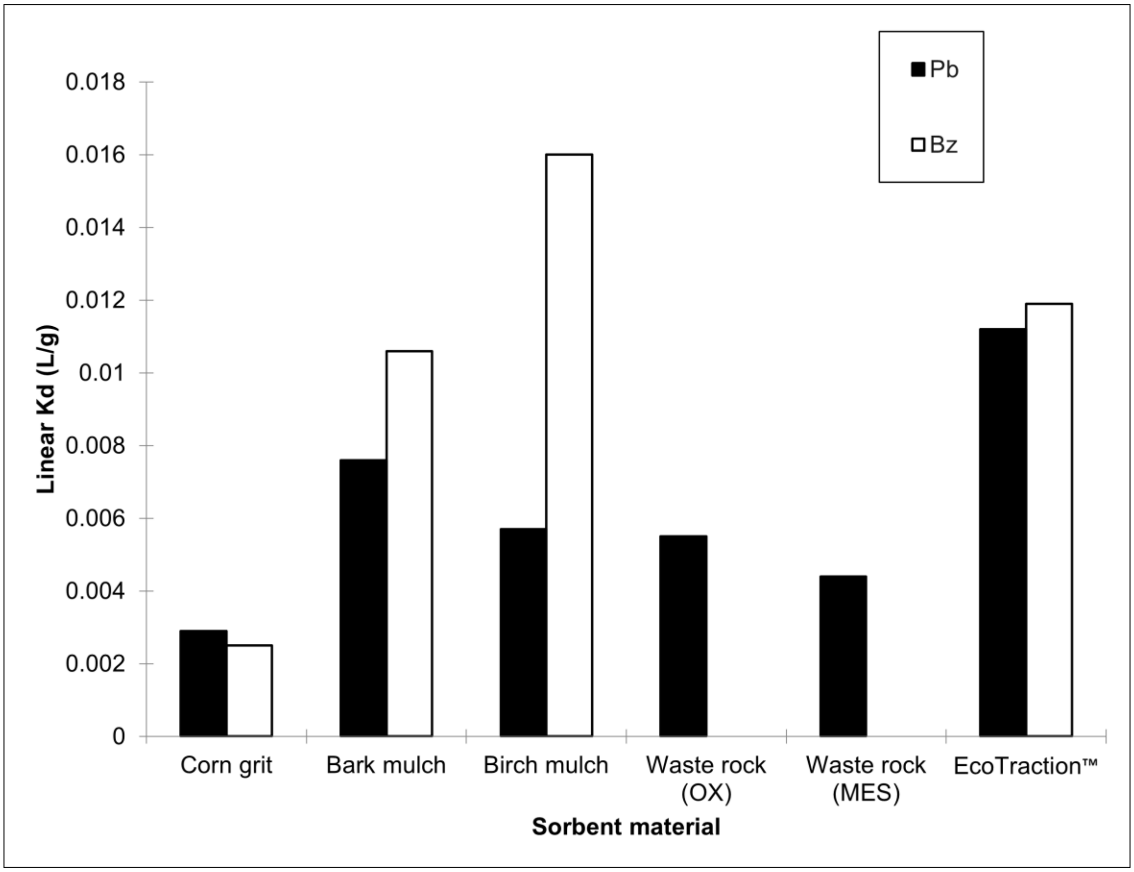


Figure 5. Estimated sorption capacities (K_d) of potential winter maintenance materials for roadside contaminants, lead (Pb) and benzene (Bz). K_d values were estimated from the slope of linear sorption isotherm models created using experimental results. The batch equilibrium tests were conducted in triplicate at fixed material mass and varying contaminant concentration. The sorption isotherm graphs used to derive K_d and a table containing K_d values and associated coefficients of determination, R^2, are included in the appendix as Figure S14 and Table S2, respectively.

3.2.2 Leaching potential

Select results for the leachate study are given in Figure 6 showing key findings. Additional results for all parameters are given graphically (Figures S15-S18) and tabularly (Tables S3-S5) in Appendix B. Acidification was observed for corn grit and birch mulch while alkalization was observed for the remaining materials (Figure S15). Alkalization was most significant for sand leachate and acidification was most significant for corn grit leachate. Increase in total organic carbon concentration was highest for the organic material leachates, with corn grit being the largest concentration change, and was minor (<5 mg/L) for the remaining materials. Increases in total phosphorus concentration were highest for organic materials leachates, with corn grit being the largest concentration change. Additionally, leachate for the OX waste rock and EcoTraction™ were observed to have a noticeable (2-3 mg/L) increase as well when compared to the control. Increases in turbidity is one of the main environmental concerns with winter maintenance abrasive use and was highest for the OX waste rock with increases up to 1800 NTU.

Upon entering a waterbody, abrasives undergo considerable dilution. Because tests were performed by studying material leachate, the analyzed solutions were more concentrated than realistic and should be considered exaggerations indicating to a potential for water quality problems to occur. It is standard WRM procedure for abrasives to be removed from the roadway, e.g., street sweeping, after winter seasons which may reduce negative water quality impacts associated with the materials entering a waterbody. However, it is important to understand what potential impacts excess material loading could have on a watershed overtime if the materials are chosen for use in WRM applications. Waterbodies that may be sensitive to slight changes of different parameters like nutrient flux may require further consideration for the materials usage and/or may want to implement more frequent removal or abrasive catchments. Anionic and cationic analyte concentrations higher than EPA or watershed standards should be considered for impact with dilution (EPA, 1995).

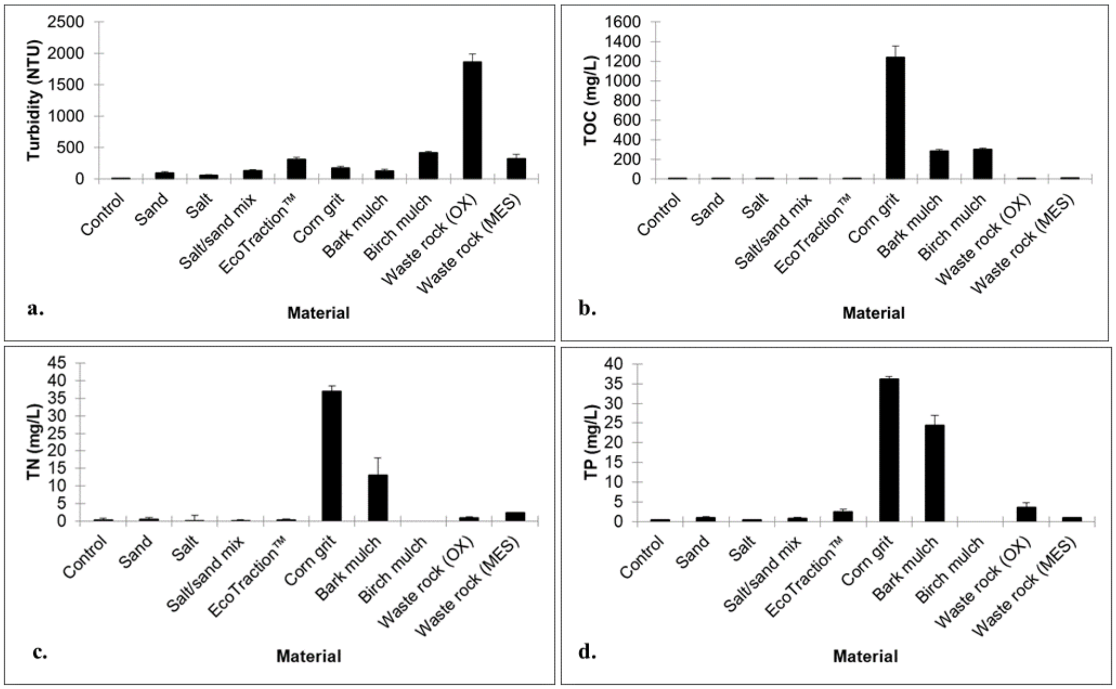


Figure 6. Material leachate results for the water quality parameters: (a) turbidity, (b) TOC, (c) TN, and (d) TP on the 3-week leaching period.

3.3 Test formulations

3.3.1 Brine infused material

To evaluate the application potential of these materials as a combination of abrasives and deicer, brine infused materials were prepared and tested. Initially, the materials' capacity to retain salt was assessed by conducting a mass balance during creation of the salt infused materials (Figure 7). Both liquid and solid salt brine material holding capacities were presented to demonstrate potential application selections. The organic candidate materials retained more salt in comparison to both the inorganic candidate materials and reference materials likely due to their higher porosity, with the bark mulch holding the most. Little difference between the measured conductivity of the collected material brine steep and control brine steep was observed suggesting no material chloride sorption affinity as also observed for chloride sorption tests. A photographic image of the infused materials can be found in Figure S19.

The organic materials (corn grit, bark mulch, birch mulch) had the largest retention/storage capacity for the brine in both wet and dry conditions which may be attributed to their more porous nature. The greater salt retention capacity of organic candidate materials show potential for their use as an alternative road salt application method to increase friction as well as de-ice with less salt use. Benefits of salt infused material application as opposed to conventional rock salt could be potential reabsorption of the salty ice melt by materials resulting in a more contained application, less environmental distribution, and lower salt dose. Additionally, the infused mulches could have potential dual use as both a friction enhancer and deicer, however further research would be needed to validate these hypotheses and to develop application methods (dosage, equipment etc.). The evaluation of infused organic materials' durability and other important application parameters is recommended. No previous studies have used physical capacity of materials for salt application, but this method may help apply lower salt dosages.

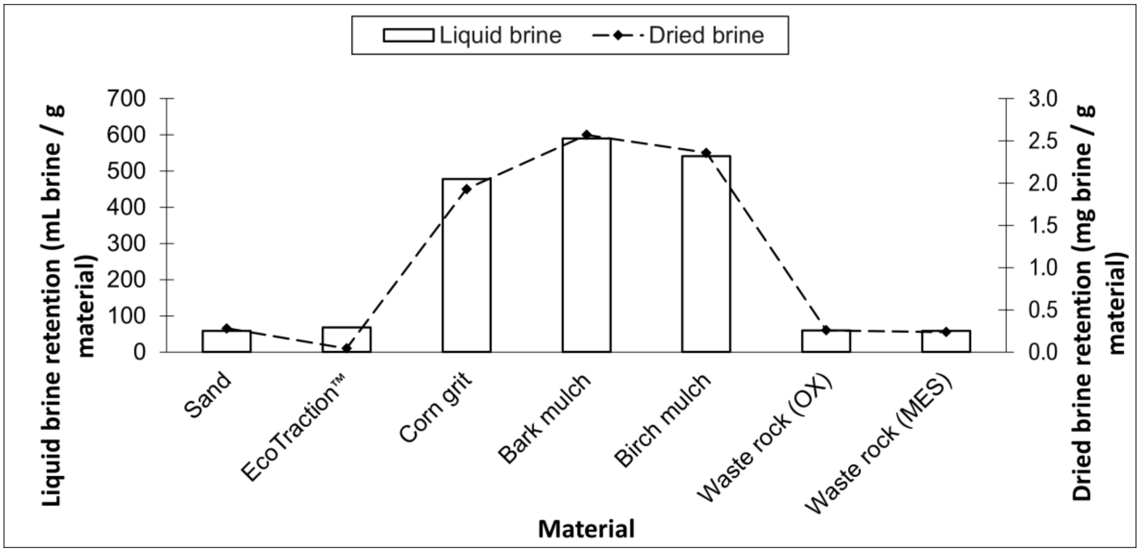


Figure 7. Salt retention of project materials for both wet (liquid brine) and dry (dried brine) conditions collected during infusing material with salt brine. The organic materials (corn grit, bark mulch, birch mulch) had the largest retention/storage capacity for the brine in both wet and dry conditions which may be attributed to their more porous nature.

3.3.2 Evaluation

The deicer performance as evaluated by percent ice melted for brine infused materials is presented in Figure 8a below. Ice melt results were presented in terms of percent ice melted in addition to ice volume melted (Figure 8b) because of the melt reabsorption by the material causing lower melt volumes collected than total melt. For the corn grit, the final melt volume was less than the total ice volume meaning that it had recaptured the melt. For the remaining deicers, specifically the mulch materials, that did not fully melt with time, the ice melt volume is considered an approximation because their resorption of the ice melt could not be determined through the experimental test procedure. The inorganics are likely close enough to their true performance because of their smaller sorption capabilities. Figure 8c presents conductivity measurements of the collected ice melt as a proxy of saltiness in melt runoff. Results showed complete ice melt for the conventional rock salt and salt/sand mixture as well as for the brine infused corn grit. It was found that the use of the corn grit deicer resulted in full ice melt with less salt application, resorption of salty ice melt, and resulting lower conductivity of collected ice melt when compared to conventional deicer and deicer mixture. The salt dosage was derived from the mass balance recorded during formulation. Application rates were standardized to MnDOT's current application rates which resulted in varying surface area coverage for the lighter materials versus the heaver materials.

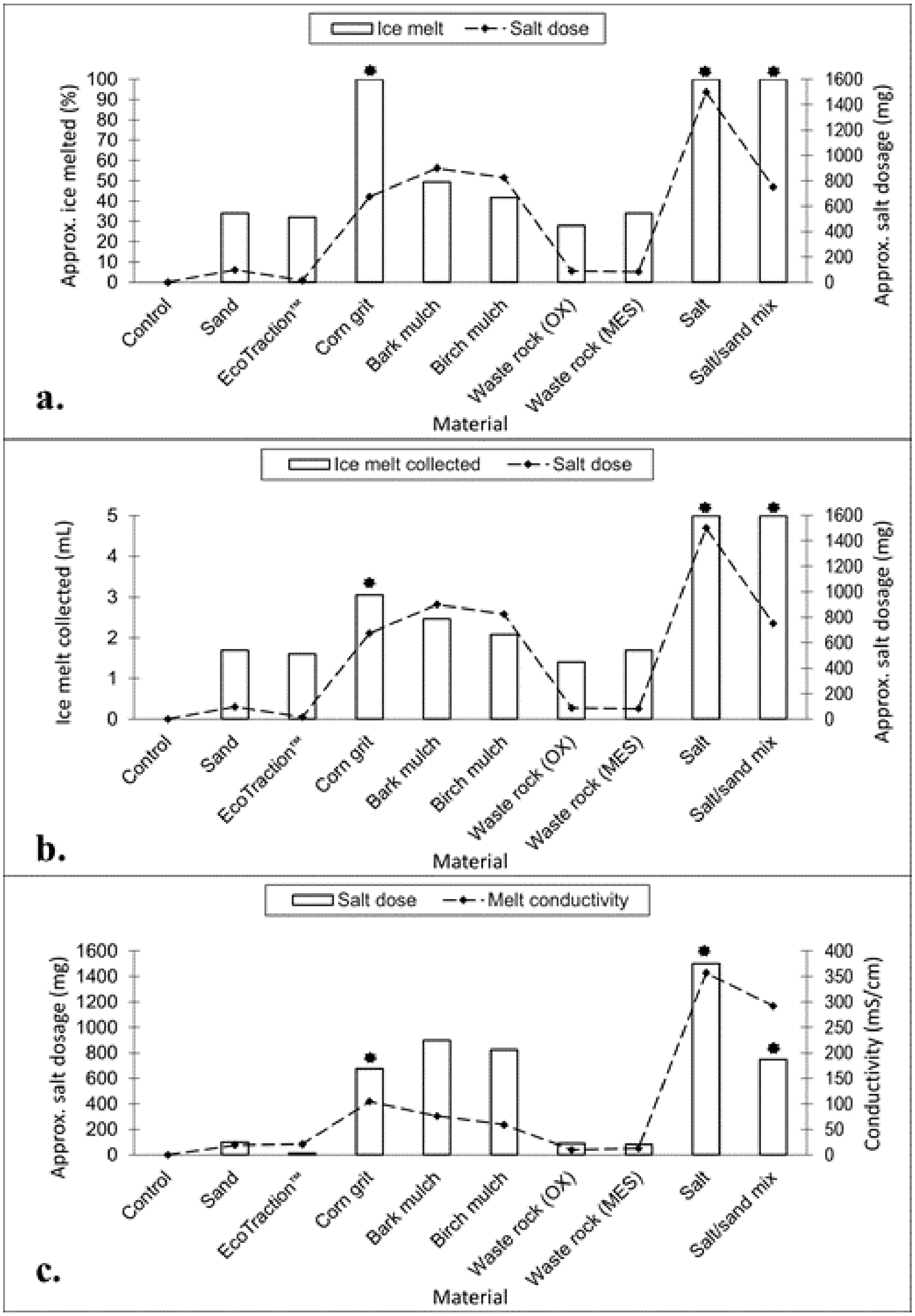


Figure 8. Brine infused material deicer performance results for (a) salt dosage of brine infused material at the standardized application rate vs percent ice melted, (b) vs volume ice melted, and (c) vs conductivity of the ice melt, over a 7-hour deicer test period and controlled 25°F temperature. For clarity, a star indicator symbol is shown above data in the deicer performance graphs for the materials that demonstrated complete ice melt. The salt dosage was derived from the mass balance recorded during formulation. Application rates were standardized to MnDOT's current application rates which resulted in varying surface area coverage for the lighter materials versus the heaver materials.

4. Conclusions

The overall goal of the research was to evaluate the potential of different locally sourced byproduct material for use as alternative materials in winter maintenance to lower road salt use and consequent environmental impacts. The goal was structured through primary objectives of (1) evaluating performance potential, (2) considering environmental impacts, and (3) suggesting final recommendations with initial results and brine infused materials. The study was conducted through physical and chemical property characterization, de-icing experiments, traction experiments, leachate study, sorption study, a brine-infusion, and recommendations. Key findings of the study in reference to the specified objectives/hypotheses were:

1. Excluding corn grit, the alternative materials were found to have either comparable or greater measures of skid resistance than conventional WRM sands and salts. Greater skid resistance was measured for both waste rocks (OX and MES), meeting the initial hypothesis. Skid resistance results for the mulch materials demonstrated potential for some form of WRM abrasive use, which was not anticipated.

2. Water quality impact potential was observed for all alternative materials through the leaching study. Increased nutrient and carbon concentration were larger for organic materials which matched expectations of the initial hypothesis. Larger turbidity increases from the OX waste rock compared to organic materials was unexpected, suggesting inorganic materials should be prepared via washing step prior to their use as abrasives. The washing procedure is comparable for conventional abrasive, sand.

3. When brine infused, all alternative materials demonstrated a degree of deicing capacity, which was unexpected for the waste rocks. Capacity was greatest for the organic materials, most notably being the corn grit, which demonstrated

similar deicing to conventional salt/sand mixtures but positively with lower chloride loading due to its retention capability with salt water.

In summary, the materials best fit in terms of winter maintenance abrasive application were found to be the inorganic waste rocks due to their preferred higher angularity, size range, and measured friction performance. An additional benefit of the waste rocks that was not directly measured in this study but could be higher solar sorption due to darker material color. This may enhance deicing. The hardness of rock material is also likely to have better longevity and durability on the roadway. Primary environmental concerns with waste rock use were found to be with turbidity that could have negative environmental consequences concerning PM10 contribution and watershed pollution/geology. The materials best fit in terms of winter maintenance deicer application were found to be the corn grits due to their higher brine retention and contaminant sorption capacity. The mulches performed secondary for friction and deicer performance but were comparable to the higher performing materials and therefore may have potential for use in both winter maintenance applications. Primary environmental concerns with organic materials were found to be potentials for nutrient and TOC loadings. This may cause negative environmental consequences for sensitive watersheds and should be appropriately considered.

The findings for this study will help to guide potential fit for the materials' application within the realm of winter road maintenance and water resource protection. In addition, the project approach and methods may be used as a reference and/or starting point for similar projects seeking to evaluate material fit. The use of alternative materials for winter road maintenance show promise for lower environmental impact, lower/controlled chloride pollution, increased friction enhancement, and beneficial reuse of industry waste material.

It is recommended that further research be done to evaluate the deicer effectiveness of the brine infused material within controlled field studies to enhance the understanding of its usage potential. It may also be useful to analyze the longevity of the material on the roadway in the pilot study to evaluate reapplication needs as well as “adhesive” potential of the material to icy road surfaces. Recommendations to DOTs include either the implementation or improvement of effective street sweeping practices to avoid potential hazards associated with these materials such as increased frequency of sweeping and/or the implementation of BMPs associated with clean-up (such as updated, more effective equipment). Material application concerns regarding parameters like material durability and environmental pollution may be addressed through application scale and cleanup protocol as important factors in determining impact, i.e., use on low vehicular speed roadways paired with road sweeping cleanup are predicted to have the best performance while minimizing environmental impact. Specific next steps recommended are:

1. Evaluate all brine infused materials for abrasive performance in a controlled field study. Partial ice melt by the brine infused material may improve abrasive performance by helping the abrasive stick to the ice surface and created increased longevity of the abrasive on the road surface.

2. Evaluate the waste rocks for abrasive performance in a controlled field study. Compare the results to their brine infused versions.

3. Evaluate deicing performance of the brine infused corn grit and bark mulches in a controlled field study.

Depending on the results from the field tests, it may be beneficial to do a cost benefit and/or life cycle analysis for top candidate materials to further assess the materials feasibility for application.

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Appendices

Appendix A - Methods

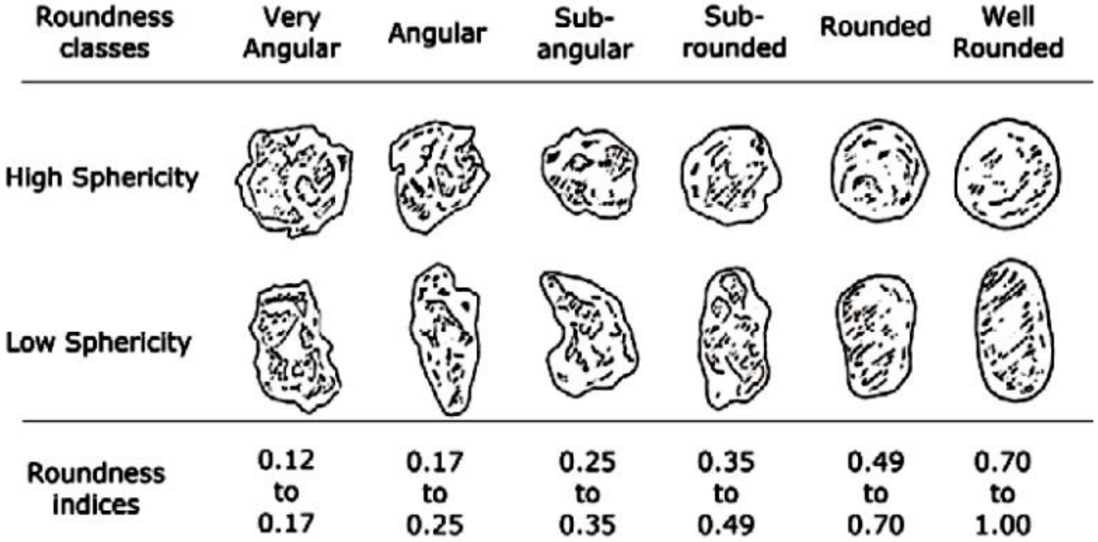


Figure S 1. Power's roundness scale used in this project as a standardized classification system for determining particle angularity, sphericity, and roundness indices. Representative material particle images used in the angularity determination were taken with a Hitachi TM3030Plus SEM. (Chu et al., 2009)

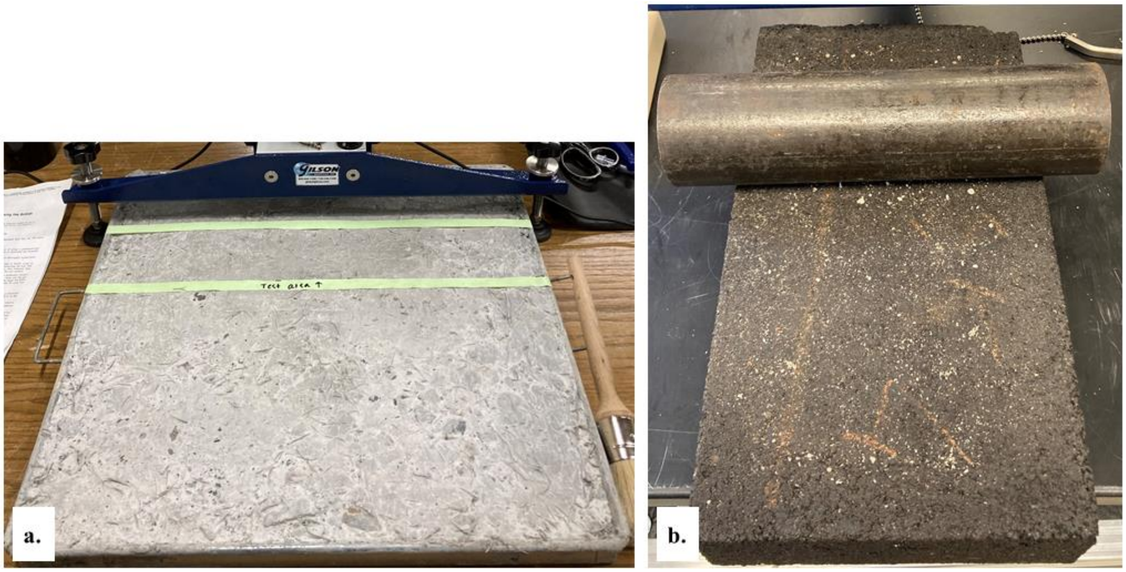


Figure S 2. (a) Concrete and (b) asphalt surfaces used for testing material supplemental friction. The concrete test surface used was fiber-reinforced concrete pavement and had a background friction of 70.3 ± 0.687 BPN throughout testing. The asphalt test surface used was hot mix asphalt and had a background friction of 80.6 ± 0.540 BPN throughout testing. Skid resistance tests were performed with a British *pendulum skid resistance tester and ASTM E303 methodology adaptations. The roller used to press loose test material prior to each test replicate can be seen on the asphalt test surface).*

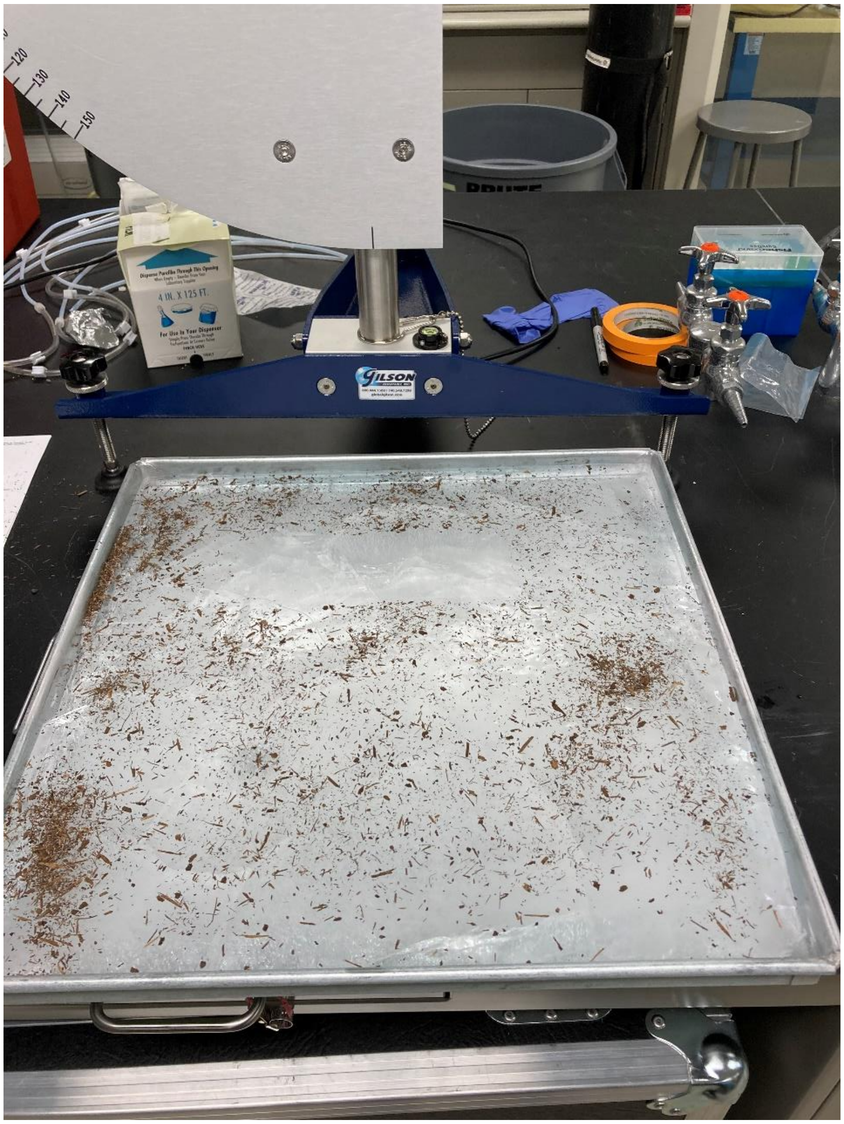


Figure S 3. Abrasive friction tests first performed in lab using a bare ice sheet as the test surface

Figure S 4. Abrasive friction field tests were attempted by creating an icy road surface

Appendix B – Results and Discussion

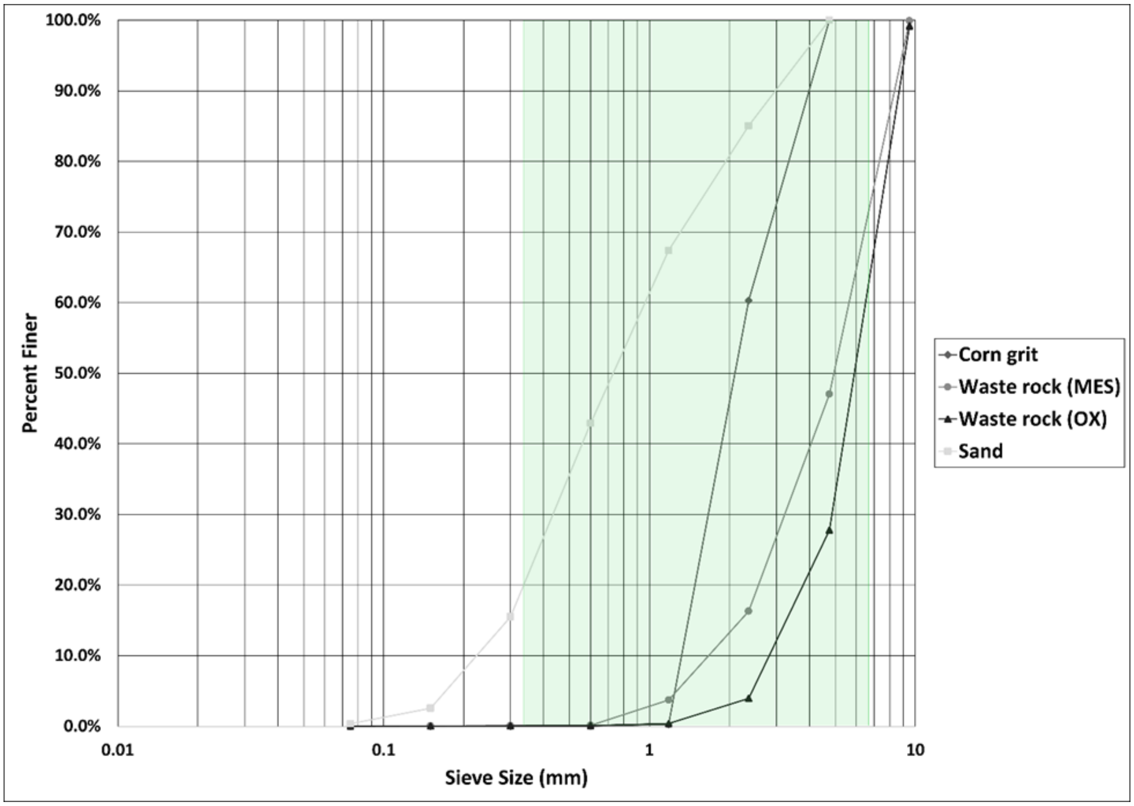


Figure S 5. Particle size distribution curves for select project materials obtained through sieve analysis. The green portion represents the particle size range recommended by MnDOT for abrasive use: Sieve No.4-No.50 (4.75-0.3 mm).

<u>Figure S5:</u>

The coefficient of uniformity, Cu, was 1.6 for corn grit indicating a narrow particle size range/uniform gradation. The extent of corn grit's particle size range fell within the indicated recommended particle size range for abrasives. The gradations of both waste rocks (OX and MES) were similar to one another. The rocks had a wider range of particle sizes when compared to corn grit but were still considered to have a uniform gradation (Cu was 2.2 and 3.1 for OX and MES, respectively). The gradation for the rocks extended out of range for the upper spec of recommended particle size.

The Cu was 4.2 for sand indicating a wide range of particle sizes present/non-uniform gradation. The gradation for sand extended out of range for the lower spec of recommended particle size.

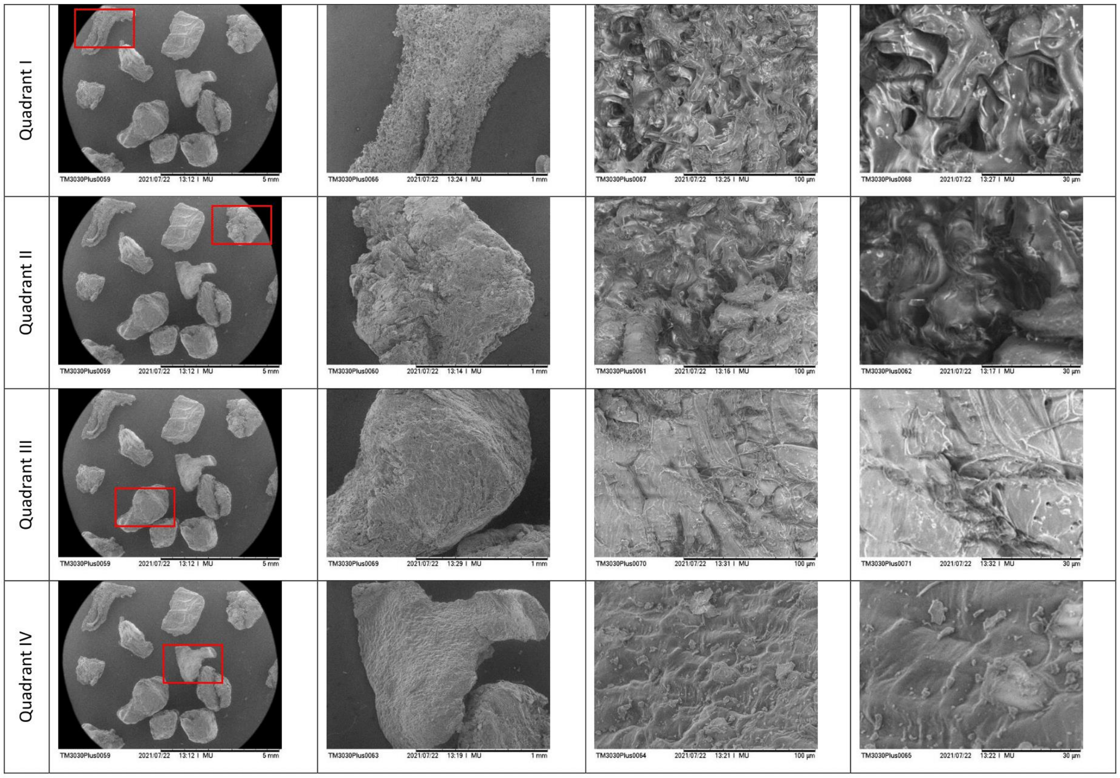


Figure S 6. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of candidate abrasive corn grit.

<u>Figure S6. Corn blast media observation notes:</u>

- Sphericity: Medium sphericity
- Angularity: Sub-rounded
- Roundness indices (Powers): 0.35-0.49
- Surface morphology: Visually porous, grooved surface texture

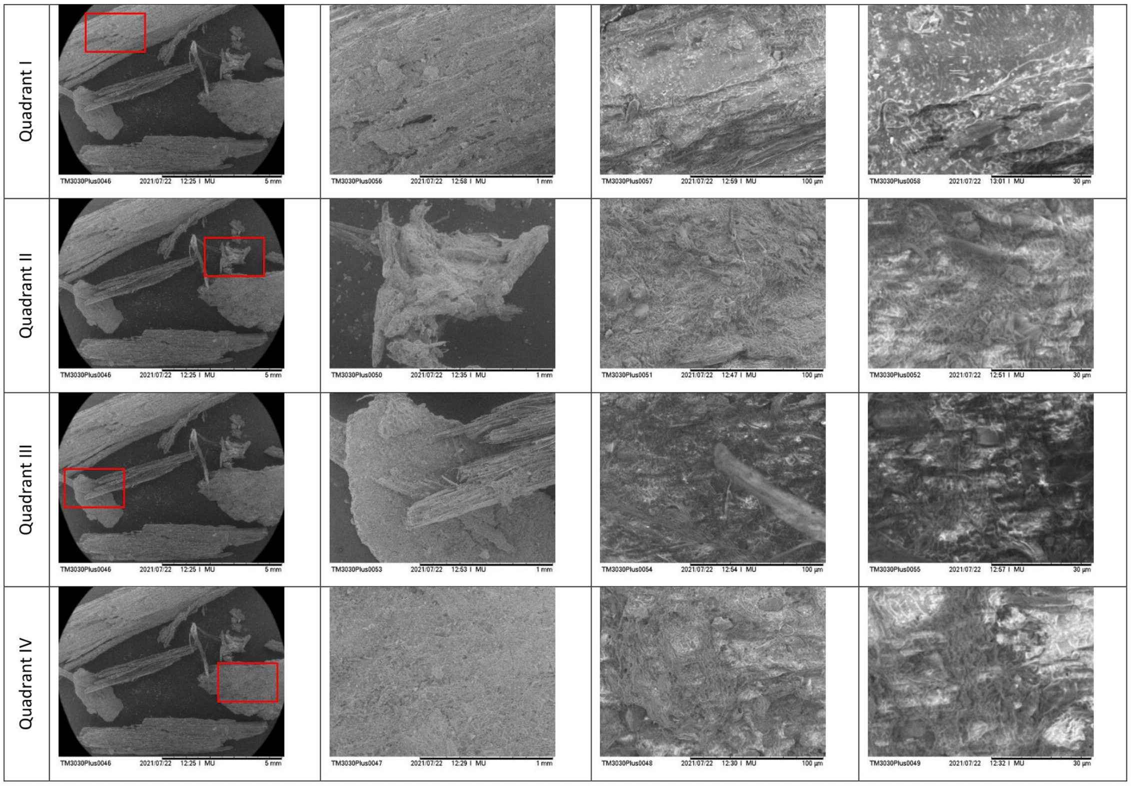


Figure S 7. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of candidate abrasive bark mulch.

Figure S7. Blended bark mulch observation notes:

- Sphericity: Low sphericity
- Angularity: Angular
- Roundness indices (Powers): 0.17-0.25
- Surface morphology: Some visual porosity, rough grooved surface texture

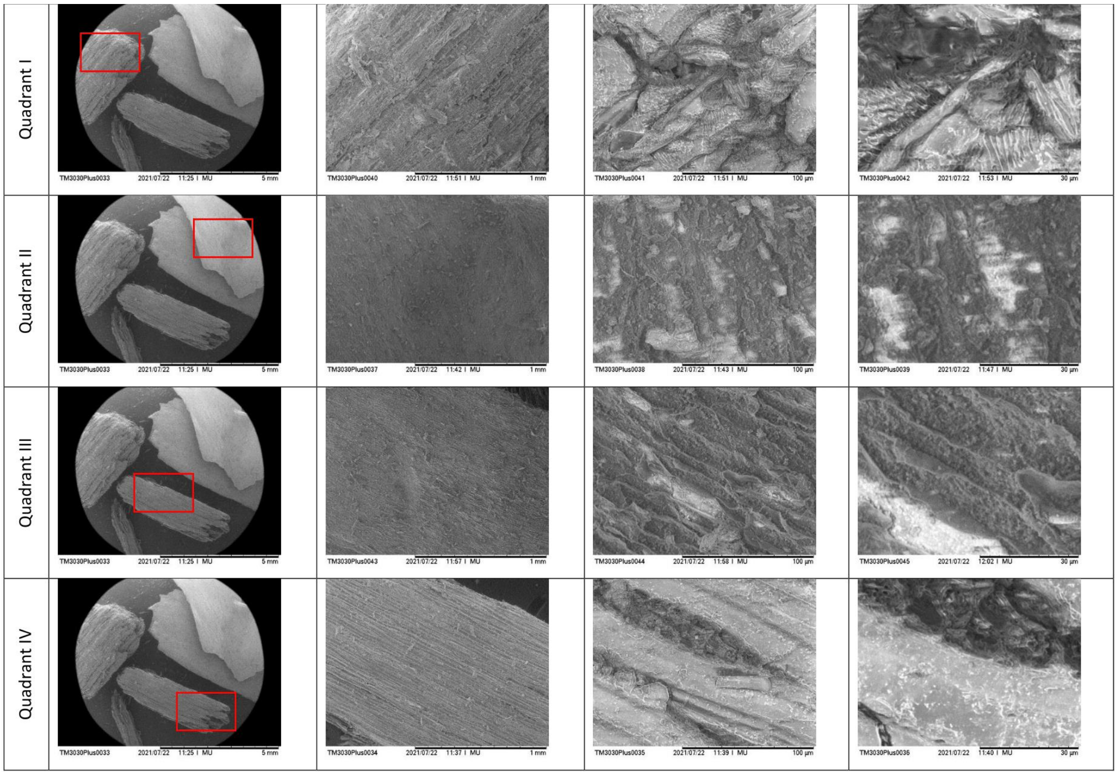


Figure S 8. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of candidate abrasive birch mulch.

<u>Figure S8. Blended birch mulch observation notes:</u>

- Sphericity: Low sphericity
- Angularity: Angular
- Roundness indices (Powers): 0.17-0.25
- Surface morphology: Visually porous, rough grooved surface texture

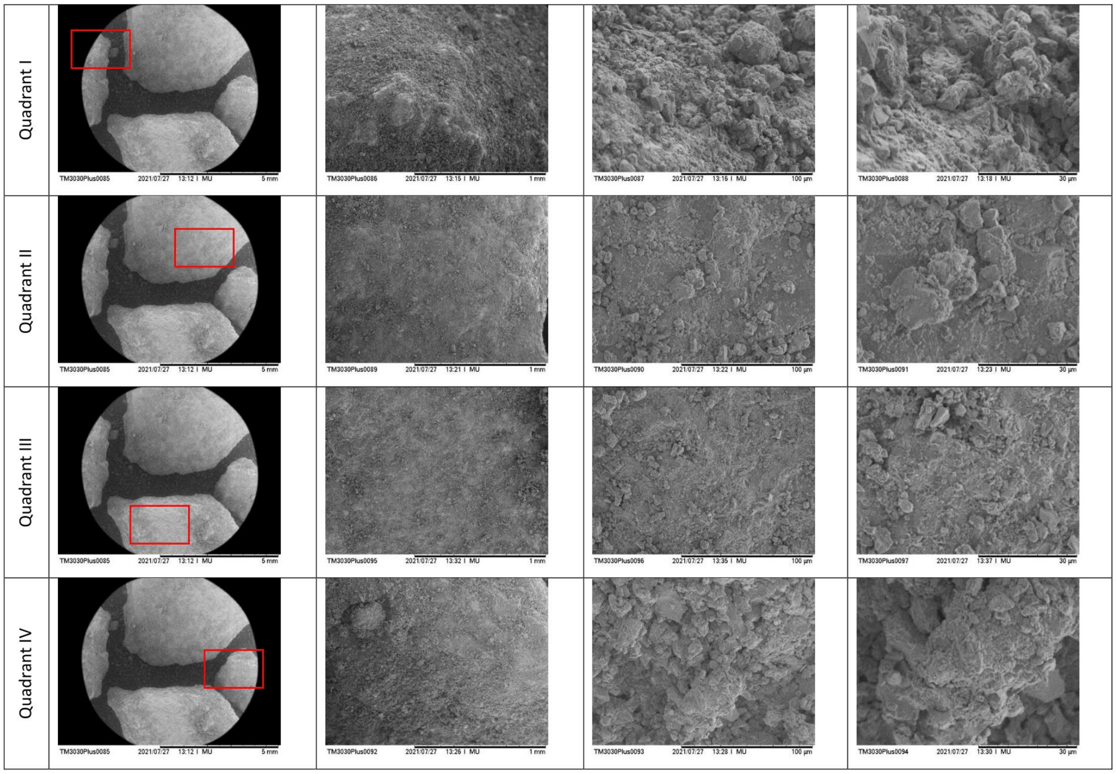


Figure S 9. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of candidate abrasive waste rock (OX).

<u>Figure S9. Waste rock (OX) observation notes:</u>

- Sphericity: Low sphericity
- Angularity: Angular
- Roundness indices (Powers): 0.17-0.25
- Surface morphology: No visual porosity, rough grooved surface texture, particle dust sticking to surface

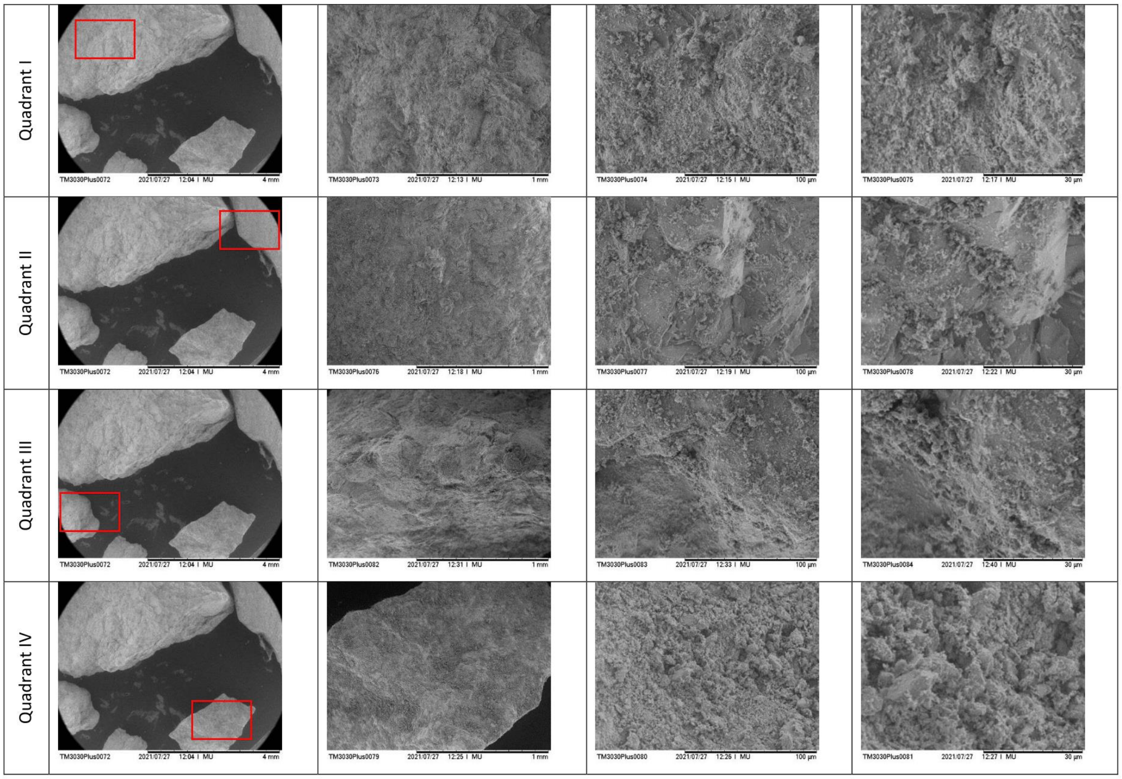


Figure S 10. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of candidate abrasive waste rock (MES).

Figure S10. Waste rock (MES) observation notes:

- Sphericity: Low sphericity
- Angularity: Very angular
- Roundness indices (Powers): 0.12-0.17
- Surface morphology: No visual porosity, very rough grooved surface texture, particle dust sticking to surface

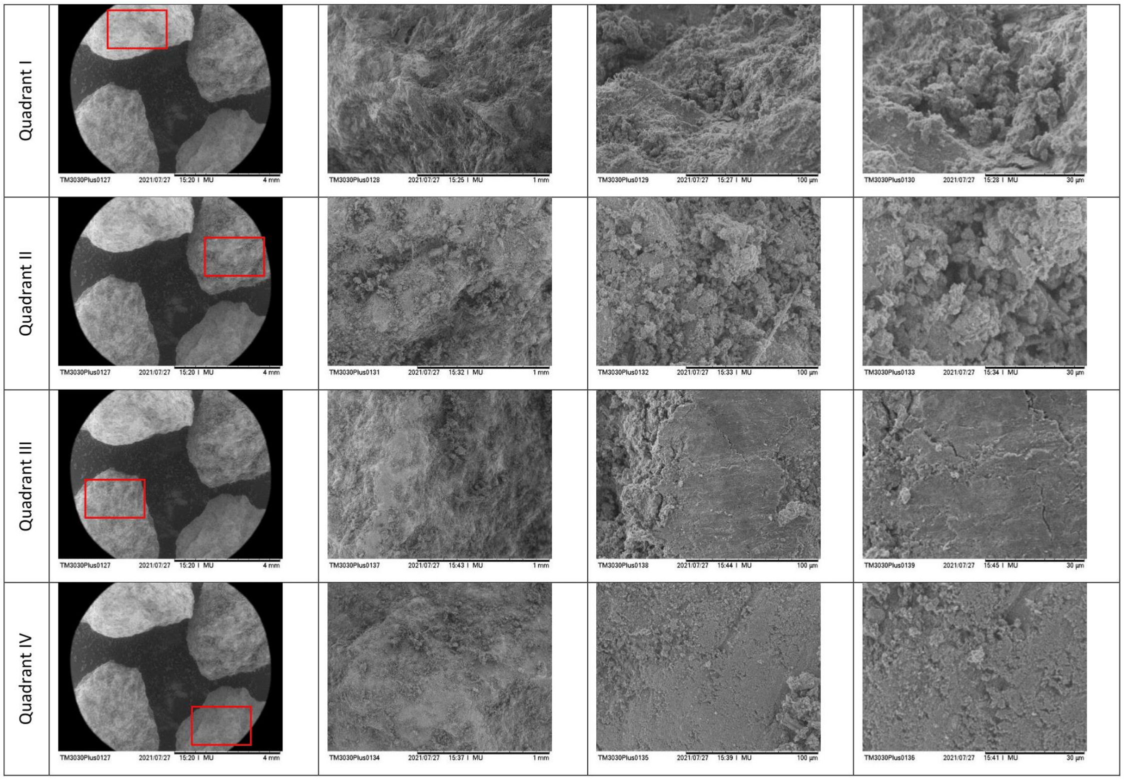


Figure S 11. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of reference abrasive EcoTraction™.

Figure S11. EcoTraction™ observation notes:

- Sphericity: Low sphericity
- Angularity: Angular
- Roundness indices (Powers): 0.17-0.25
- Surface morphology: Some visual porosity, rough grooved surface texture, particle dust sticking to surface

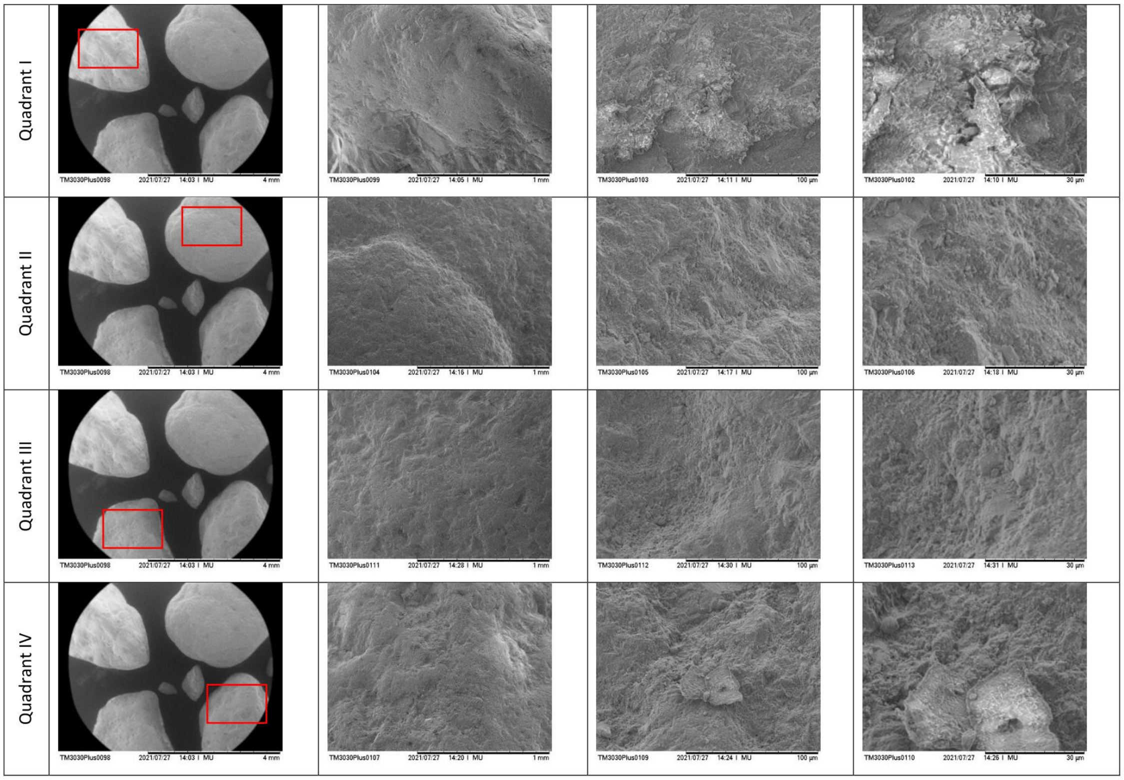


Figure S 12. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of reference abrasive sand

Figure S12. MnDOT sand observation notes:

- Sphericity: Medium sphericity
- Angularity: Sub-rounded
- Roundness indices (Powers): 0.35-0.49
- Surface morphology: No visual porosity, smoother surface texture with small grooves

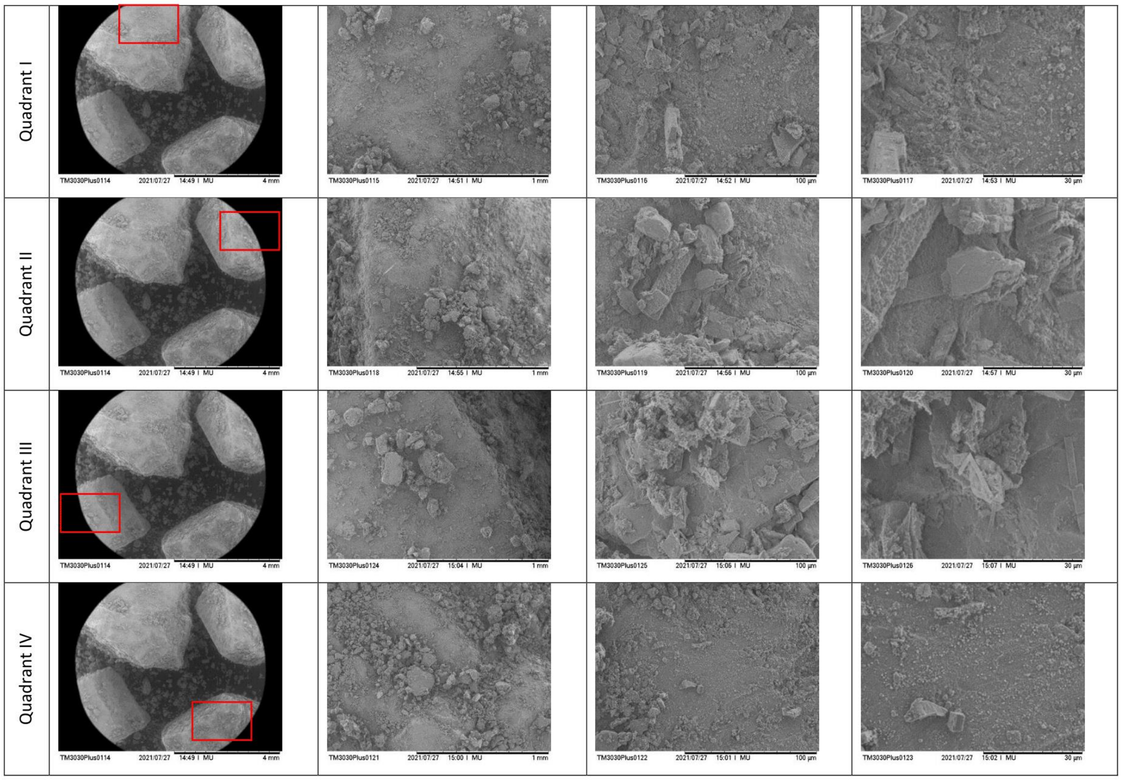


Figure S 13. Scanning electron microscopy images and associated observation notes taken to characterize material sphericity, angularity, roundness (Powers) index, porosity, and surface texture morphological features of reference abrasive rock salt

Figure S13. MnDOT salt observation notes:

- Sphericity: Medium sphericity
- Angularity: Sub-rounded
- Roundness indices (Powers): 0.35-0.49
- Surface morphology: No visual porosity, smooth surface textures with particle dust sticking to surface

Table S 1. Average elemental concentrations of digested project materials (n=3) for 27 elements in units of mg/g and percentage for the top and bottom table, respectively.

Sample ID	***Al***	***As***	***B***	***Ba***	***Be***	***Ca***	***Cd***	***Co***	***Cr***	***Cu***	***Fe***	***K***	***Li***	***Mg***	***Mn***	***Mo***	***Na***	***Ni***	***P***	***Pb***	***Rb***	***S***	***Si***	***Sr***	***Ti***	***V***	***Zn***
MnDOT sand	2.21	0.00	0.01	0.01	0.00	6.99	0.00	0.01	0.05	0.03	12.07	0.15	0.00	2.11	0.15	0.00	0.40	0.39	0.37	0.00	0.00	0.06	0.61	0.03	0.16	0.01	0.03
Waste rock (MES)	1.80	0.00	0.11	0.00	0.00	4.93	0.00	0.00	0.00	0.00	112.00	0.35	0.00	7.62	1.57	0.00	0.12	0.00	0.16	0.00	0.00	0.09	0.30	0.02	0.03	0.02	0.01
Waste rock (OX)	0.31	0.01	0.04	0.01	0.00	3.42	0.00	0.01	0.05	0.00	75.13	0.18	0.00	0.16	3.76	0.00	0.08	0.28	0.04	0.00	0.00	0.04	0.69	0.02	0.01	0.01	0.00
Blended bark mulch	0.29	0.00	0.01	0.06	0.00	13.36	0.00	0.00	0.00	0.02	0.96	0.76	0.00	0.65	0.24	0.00	0.30	0.00	0.27	0.00	0.00	0.16	0.28	0.06	0.01	0.00	0.09
Blended birch mulch	0.58	0.00	0.00	0.02	0.00	10.27	0.00	0.00	0.01	0.01	0.40	0.62	0.00	0.23	0.18	0.00	0.19	0.03	0.12	0.00	0.00	0.09	0.14	0.05	0.00	0.00	0.06
Corn blast media	0.01	0.00	0.00	0.00	0.00	3.50	0.00	0.00	0.00	0.01	0.00	4.12	0.00	0.17	0.00	0.00	0.08	0.00	0.18	0.00	0.00	0.09	0.23	0.02	0.00	0.00	0.00

Sample ID	***Al***	***As***	***B***	***Ba***	***Be***	***Ca***	***Cd***	***Co***	***Cr***	***Cu***	***Fe***	***K***	***Li***	***Mg***	***Mn***	***Mo***	***Na***	***Ni***	***P***	***Pb***	***Rb***	***S***	***Si***	***Sr***	***Ti***	***V***	***Zn***	***Other***
MnDOT sand	0.22	0.00	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.00	1.21	0.02	0.00	0.21	0.02	0.00	0.04	0.04	0.04	0.00	0.00	0.01	0.06	0.00	0.02	0.00	0.00	97.41
Waste rock (MES)	0.18	0.00	0.01	0.00	0.00	0.49	0.00	0.00	0.00	0.00	11.20	0.03	0.00	0.76	0.16	0.00	0.01	0.00	0.02	0.00	0.00	0.01	0.03	0.00	0.00	0.00	0.00	87.09
Waste rock (OX)	0.03	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.01	0.00	7.51	0.02	0.00	0.02	0.38	0.00	0.01	0.03	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	91.58
Blended bark mulch	0.03	0.00	0.00	0.01	0.00	1.34	0.00	0.00	0.00	0.00	0.10	0.08	0.00	0.06	0.02	0.00	0.03	0.00	0.03	0.00	0.00	0.02	0.03	0.01	0.00	0.00	0.01	98.25
Blended birch mulch	0.06	0.00	0.00	0.00	0.00	1.03	0.00	0.00	0.00	0.00	0.04	0.06	0.00	0.02	0.02	0.00	0.02	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.01	98.70
Corn blast media	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.02	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.00	99.16

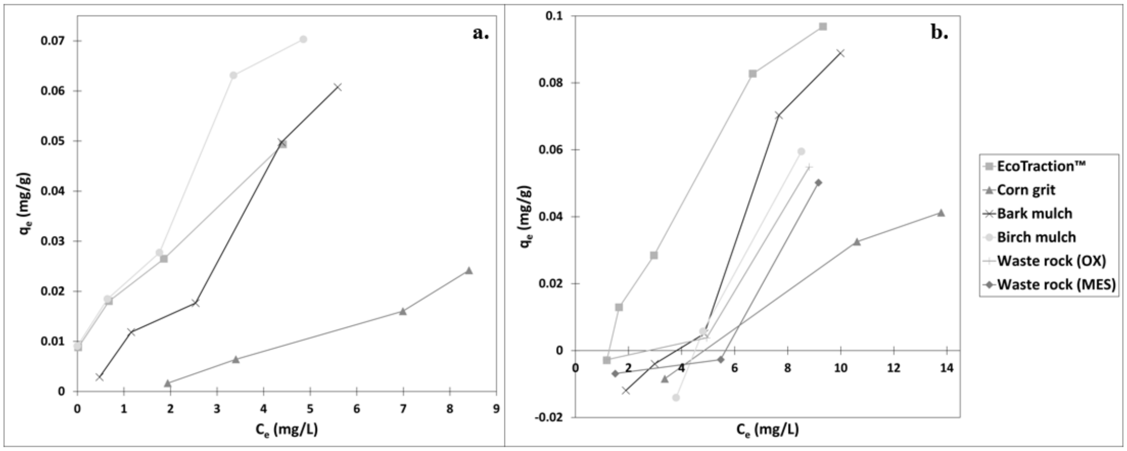
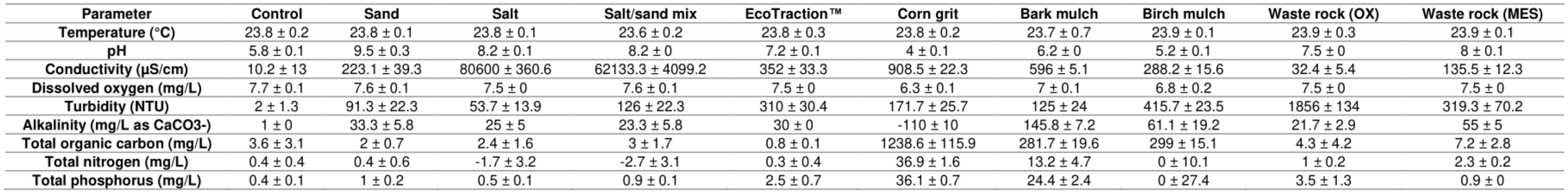


Figure S 14. Linear sorption isotherms of potential winter maintenance material for roadside contaminants (a) benzene and (b) lead, obtained experimentally through batch equilibrium tests at fixed mass and varying concentration. Sorption capacity values, K_d, were determined graphically using the slope estimations of respective isotherms.

Table S 2. Sorption capacity, K_d, results and associated R^2 values for potential winter maintenance material and roadside contaminants, lead and benzene, obtained experimentally through batch equilibrium tests at fixed mass and varying concentration. Results were obtained graphically using the slope estimations of linear isotherms (Figure S14).

Material	**Lead**		**Benzene**	
	K_d	**R^2**	**K_d**	**R^2**
Corn grit	0.003	0.889	0.003	0.970
Bark mulch	0.008	0.807	0.011	0.984
Birch mulch	0.006	0.910	0.016	0.971
Waste rock (OX)	0.006	0.883	-	-
Waste rock (MES)	0.004	0.760	-	-
EcoTraction™	0.011	0.981	0.012	0.943

Table S 3. Material environmental leachate results for water quality parameters at the final sampling period, 3-weeks.



Parameter	Control	Sand	Salt	Salt/sand mix	EcoTraction™	Corn grit	Bark mulch	Birch mulch	Waste rock (OX)	Waste rock (MES)
Temperature (°C)	23.8 ± 0.2	23.8 ± 0.1	23.8 ± 0.1	23.6 ± 0.2	23.8 ± 0.3	23.8 ± 0.2	23.7 ± 0.7	23.9 ± 0.1	23.9 ± 0.3	23.9 ± 0.1
pH	5.8 ± 0.1	9.5 ± 0.3	8.2 ± 0.1	8.2 ± 0	7.2 ± 0.1	4 ± 0.1	6.2 ± 0	5.2 ± 0.1	7.5 ± 0	8 ± 0.1
Conductivity (µS/cm)	10.2 ± 13	223.1 ± 39.3	80600 ± 360.6	62133.3 ± 4099.2	352 ± 33.3	908.5 ± 22.3	596 ± 5.1	288.2 ± 15.6	32.4 ± 5.4	135.5 ± 12.3
Dissolved oxygen (mg/L)	7.7 ± 0.1	7.6 ± 0.1	7.5 ± 0	7.6 ± 0.1	7.5 ± 0	6.3 ± 0.1	7 ± 0.1	6.8 ± 0.2	7.5 ± 0	7.5 ± 0
Turbidity (NTU)	2 ± 1.3	91.3 ± 22.3	53.7 ± 13.9	126 ± 22.3	310 ± 30.4	171.7 ± 25.7	125 ± 24	415.7 ± 23.5	1856 ± 134	319.3 ± 70.2
Alkalinity (mg/L as CaCO3-)	1 ± 0	33.3 ± 5.8	25 ± 5	23.3 ± 5.8	30 ± 0	-110 ± 10	145.8 ± 7.2	61.1 ± 19.2	21.7 ± 2.9	55 ± 5
Total organic carbon (mg/L)	3.6 ± 3.1	2 ± 0.7	2.4 ± 1.6	3 ± 1.7	0.8 ± 0.1	1238.6 ± 115.9	281.7 ± 19.6	299 ± 15.1	4.3 ± 4.2	7.2 ± 2.8
Total nitrogen (mg/L)	0.4 ± 0.4	0.4 ± 0.6	-1.7 ± 3.2	-2.7 ± 3.1	0.3 ± 0.4	36.9 ± 1.6	13.2 ± 4.7	0 ± 10.1	1 ± 0.2	2.3 ± 0.2
Total phosphorus (mg/L)	0.4 ± 0.1	1 ± 0.2	0.5 ± 0.1	0.9 ± 0.1	2.5 ± 0.7	36.1 ± 0.7	24.4 ± 2.4	0 ± 27.4	3.5 ± 1.3	0.9 ± 0

Table S 4. Material environmental leachate results for select common anions detected at the final sampling period, 3-weeks.

Anion	Sand concentration (mg/L)	EcoTraction™ concentration (mg/L)	Corn grit concentration (mg/L)	Bark mulch concentration (mg/L)	Birch mulch concentration (mg/L)	Waste rock (OX) concentration (mg/L)	Waste rock (MES) concentration (mg/L)
F^-	0.132 ± 0.014	3.686 ± 0.231	96.62 ± 11.547	20.723 ± 0.38	5.278 ± 1.449	0.268 ± 0.315	0.041 ± 0.071
Cl^-	36.093 ± 2.313	0.336 ± 0.582	92.754 ± 6.154	4.72 ± 4.022	16.363 ± 0.853	0.499 ± 0.243	0.544 ± 0.289
NO_2^-	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0.01 ± 0.017
Br^-	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
NO_3^-	0.152 ± 0.171	0.93 ± 0.728	2.341 ± 1.669	0.296 ± 0.265	0.345 ± 0.307	0.088 ± 0.153	6.219 ± 0.228
PO_4^{3-}	0 ± 0	0.392 ± 0.679	6.092 ± 10.551	8.642 ± 7.033	10.443 ± 8.457	0.192 ± 0.192	0.164 ± 0.285
SO_4^{2-}	23.158 ± 22.85	112.847 ± 7.72	2.343 ± 1.218	1.195 ± 1.064	5.667 ± 0.233	1.06 ± 0.192	6.314 ± 1.102
PO_4^{3-}	0 ± 0	0.392 ± 0.679	6.092 ± 10.551	8.642 ± 7.033	10.443 ± 8.457	0.192 ± 0.192	0.164 ± 0.285

Table S 5. Material environmental leachate results for select cations detected at the final sampling period, 3-weeks.

Element	**Sand concentration (mg/L)**	**EcoTraction™ concentration (mg/L)**	**Corn grit concentration (mg/L)**	**Bark mulch concentration (mg/L)**	**Birch mulch concentration (mg/L)**	**Waste rock (OX) concentration (mg/L)**	**Waste rock (MES) concentration (mg/L)**
F^-	0.132 ± 0.014	3.686 ± 0.231	96.62 ± 11.547	20.723 ± 0.38	5.278 ± 1.449	0.268 ± 0.315	0.041 ± 0.071
Al	3.309 ± 0.491	16.57 ± 0.868	0.024 ± 0.004	0.655 ± 0.41	0.104 ± 0.012	3.089 ± 0.294	1.04 ± 0.156
As	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
B	0 ± 0	0 ± 0	0 ± 0	0.134 ± 0.013	0.154 ± 0.011	0 ± 0	0.09 ± 0.003
Ba	0.011 ± 0.001	0.655 ± 0.023	0.015 ± 0.006	0.625 ± 0.059	0.428 ± 0.039	0.035 ± 0.004	0.01 ± 0.001
Be	0 ± 0	0.001 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Ca	3.379 ± 1.618	11.109 ± 0.589	4.701 ± 2.811	104.193 ± 3.761	27.087 ± 2.165	4.943 ± 0.529	4.991 ± 0.542
Cd	0 ± 0	0 ± 0	0 ± 0	0.004 ± 0.001	0.003 ± 0.001	0.002 ± 0.001	0 ± 0
Co	0.011 ± 0.004	0.003 ± 0	0.003 ± 0.001	0.005 ± 0	0.004 ± 0	0.039 ± 0.003	0.019 ± 0.003
Cr	0.01 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	0.005 ± 0.001	0.003 ± 0	0.018 ± 0.002	0.005 ± 0
Cu	0.034 ± 0.006	0.005 ± 0.001	0.022 ± 0.004	0.018 ± 0.01	0.041 ± 0.002	0.046 ± 0.013	0.025 ± 0.002
Fe	5.901 ± 0.841	4.981 ± 0.389	0.366 ± 0.037	2.584 ± 0.622	0.384 ± 0.048	22.506 ± 3.008	42.857 ± 6.609
K	0.642 ± 0.131	25.064 ± 1.349	281.498 ± 7.2	52.854 ± 0.949	46.74 ± 2.435	1.496 ± 0.224	9.067 ± 1.188
Li	0 ± 0	0.02 ± 0.001	0 ± 0	0.005 ± 0.001	0.007 ± 0.001	0.007 ± 0.001	0 ± 0
Mg	2.051 ± 0.206	1.407 ± 0.08	8.596 ± 0.274	17.93 ± 0.394	6.796 ± 0.512	3.999 ± 0.461	12.427 ± 1.116
Mn	0.175 ± 0.032	0.162 ± 0.009	0.124 ± 0.004	2.795 ± 0.176	3.449 ± 0.228	7.687 ± 1.004	1.6 ± 0.276
Mn	0 ± 0	0.004 ± 0.001	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Na	45.329 ± 5.078	56.921 ± 1.608	0.62 ± 0.05	8.021 ± 0.173	10.159 ± 0.547	0.451 ± 0.053	5.525 ± 0.477
Ni	0.013 ± 0.003	0 ± 0	0 ± 0	0.005 ± 0.001	0.003 ± 0.001	0.011 ± 0.002	0.005 ± 0
P	0.151 ± 0.04	0.138 ± 0.017	10.752 ± 0.355	6.666 ± 0.577	7.272 ± 0.535	0.099 ± 0.013	0.108 ± 0.018
Pb	0 ± 0	0.029 ± 0.003	0 ± 0	0 ± 0	0 ± 0	0.011 ± 0.002	0.007 ± 0.002
Rb	0 ± 0	0.041 ± 0.003	0.094 ± 0.002	0.082 ± 0.004	0.06 ± 0.004	0.002 ± 0	0.004 ± 0.001
S	6.421 ± 6.909	41.848 ± 1.593	3.121 ± 0.172	0.522 ± 0.015	2.56 ± 0.098	0.37 ± 0.087	2.686 ± 0.284
Si	8.607 ± 0.871	23.713 ± 0.376	3.254 ± 0.205	4.239 ± 0.481	0.925 ± 0.109	10.028 ± 0.964	8.511 ± 0.13
Sr	0.036 ± 0.024	0.034 ± 0.002	0.021 ± 0.005	0.494 ± 0.015	0.137 ± 0.012	0.029 ± 0.004	0.041 ± 0.004
Ti	0.163 ± 0.014	0.053 ± 0.003	0 ± 0	0.022 ± 0.01	0.006 ± 0.001	0.119 ± 0.01	0.019 ± 0.002
V	0.018 ± 0.005	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0.007 ± 0.002	0.013 ± 0.002
Zn	2.37 ± 0.682	0.049 ± 0.003	0.315 ± 0.026	0.357 ± 0.129	0.66 ± 0.038	0.034 ± 0.004	0.021 ± 0.008

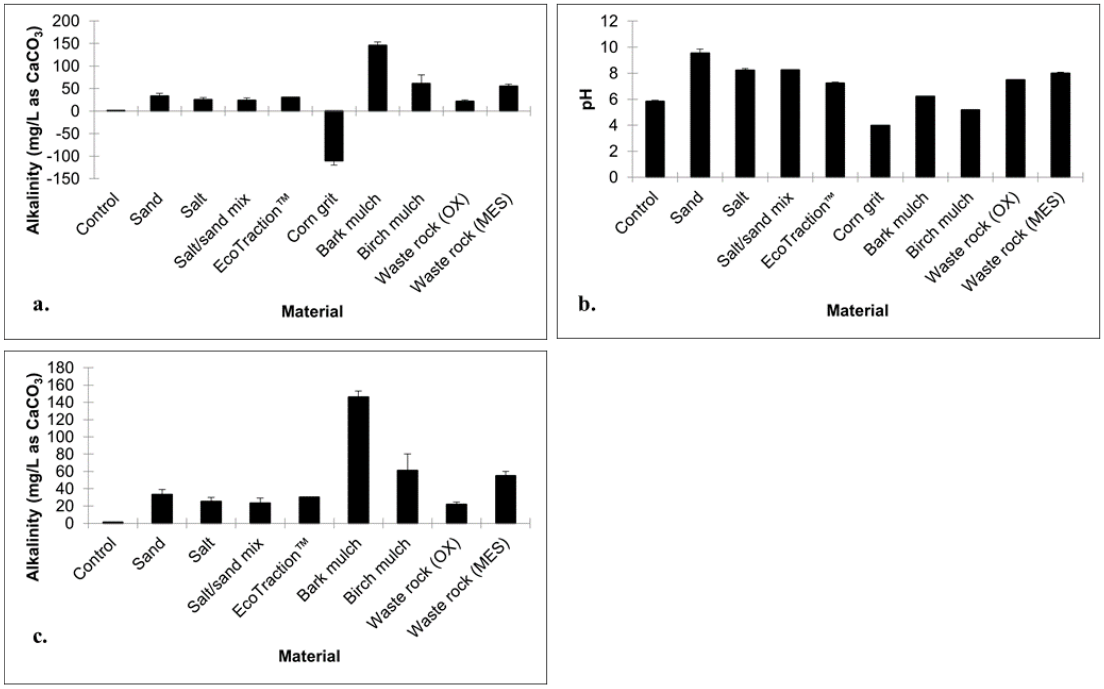


Figure S 15. Material leachate results for the water quality parameters: (a) alkalinity, (b) pH, and (c) alkalinity with scaled-axis on the 3-week leaching period.

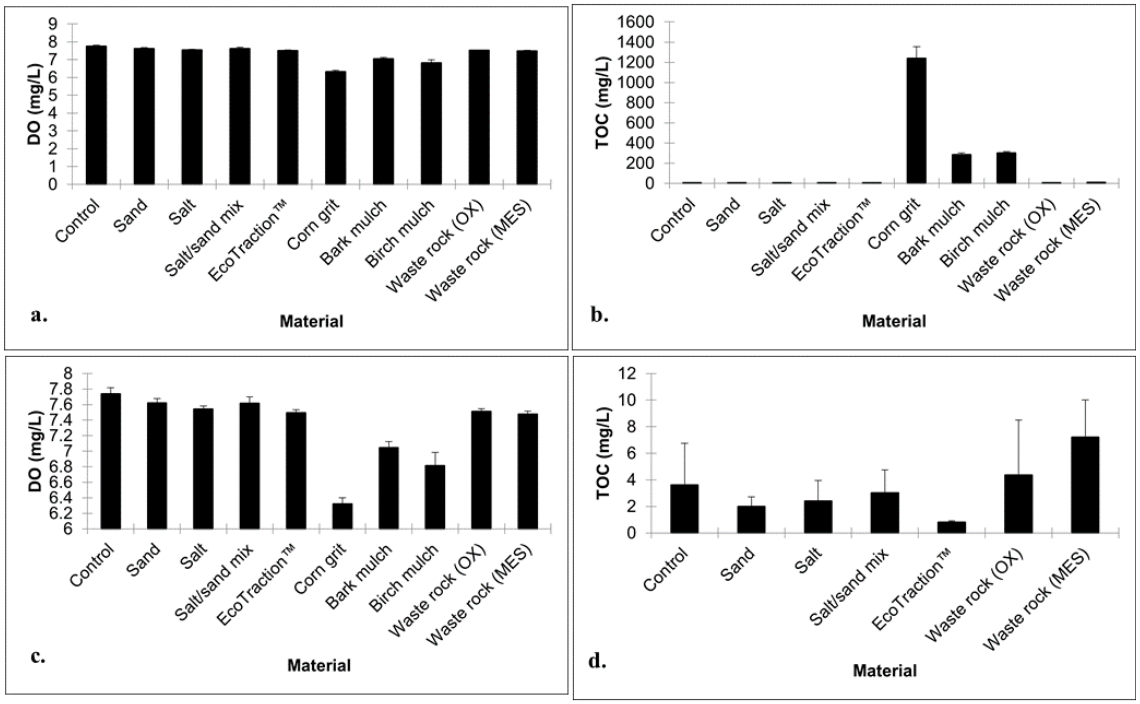


Figure S 16. Material leachate results for the water quality parameters: (a) DO, (b) TOC, (c) DO with scaled-axis, and (d) TOC with scaled-axis on the 3-week leaching period.

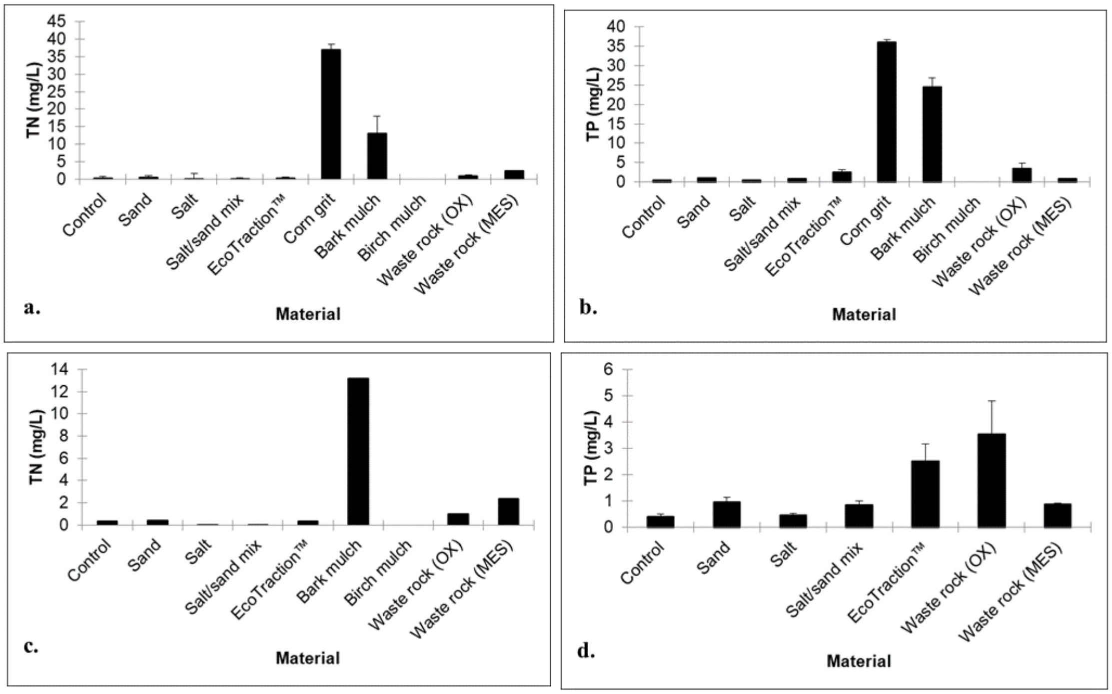


Figure S 17. Material leachate results for the water quality parameters: (a) TN, (b) TP, (c) TN with scaled-axis, and (d) TP with scaled-axis on the 3-week leaching period.

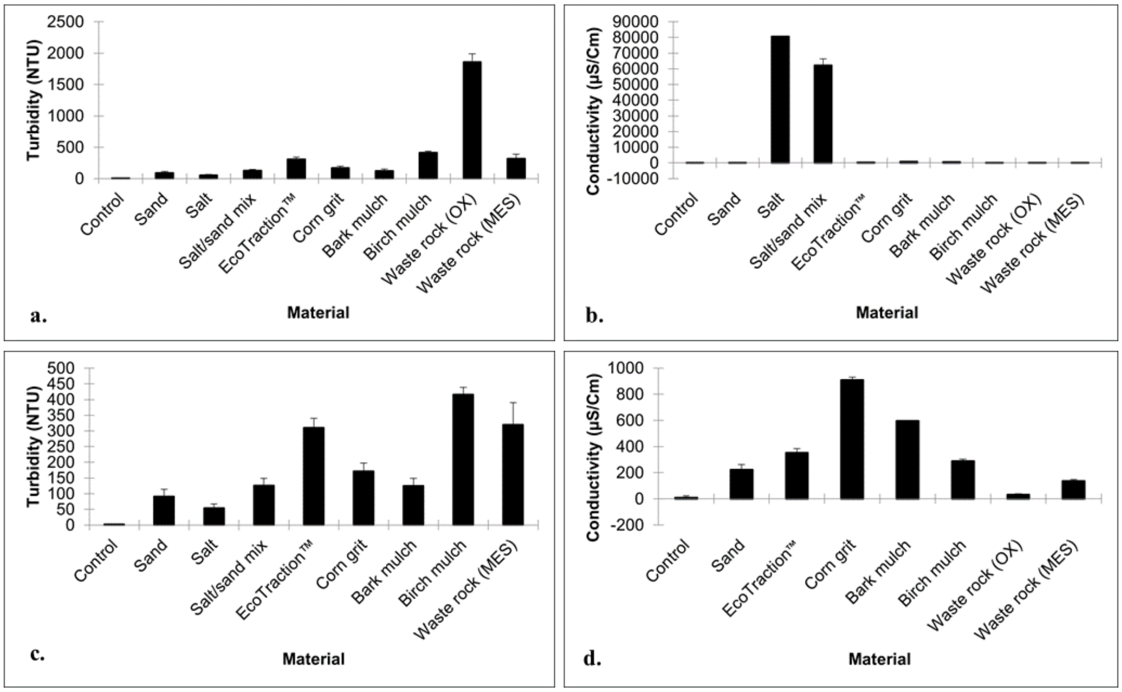


Figure S 18. Material leachate results for the water quality parameters: (a) turbidity, (b) conductivity, (c) turbidity with scaled-axis, and (d) conductivity with scaled-axis on the 3-week leaching period.

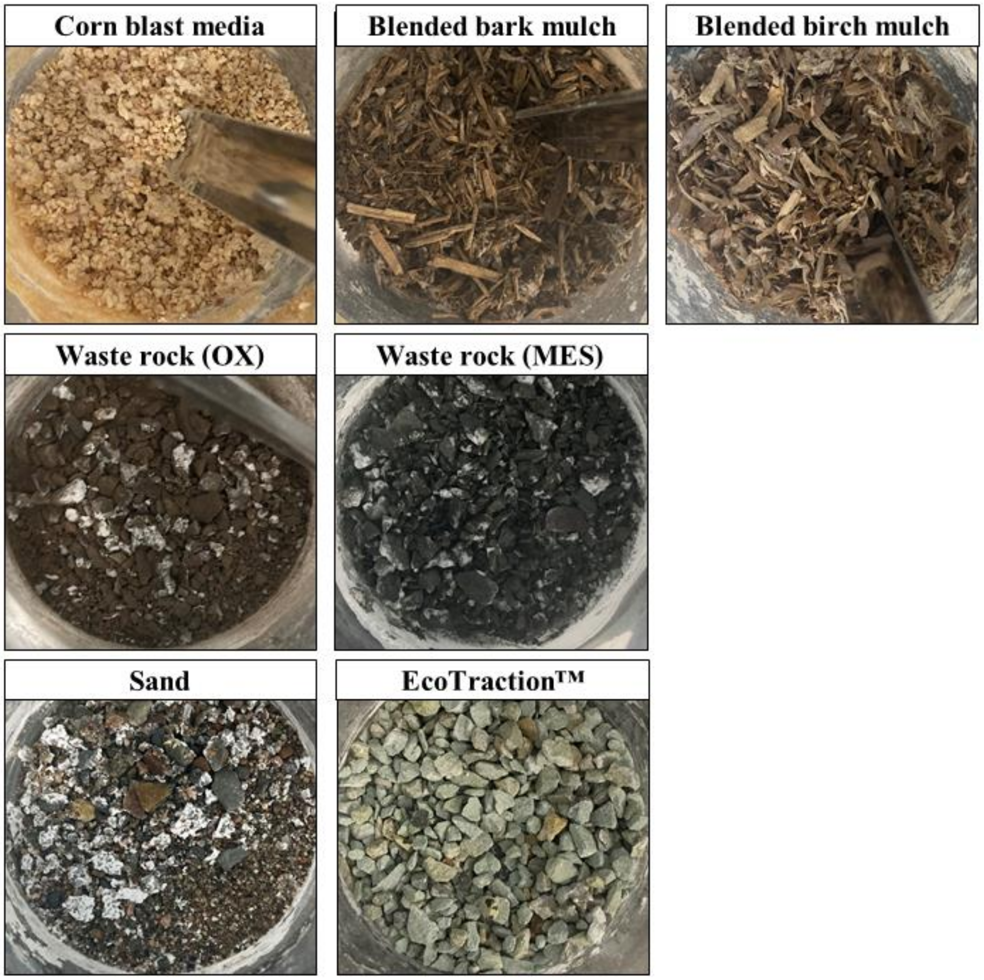


Figure S 19. Brine infused versions of project material.