Final Report

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solid earth

Implementation of Solid Earth Inc. for Soil Stabilization, Dust, Erosion Mitigation and Eco Paving

The New Economy Initiative (NEI) Science and Technology Centers (STCs) Arizona State University

By

Jolina J. Karam, Ph.D.

Carlos J. Obando, Ph.D.

Jose R. Medina, Ph.D, P.E.

Kamil E. Kaloush, Ph.D, P.E.

School of Sustainable Engineering and the Built Environment

ASU Ira A. Fulton Schools of Engineering
Arizona State University

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Introduction

Soil stabilization is a critical engineering practice essential for constructing durable and reliable infrastructure on existing soil conditions. By enhancing soil properties, stabilization addresses a range of challenges, including slope stability, surface protection, and resistance to weathering. Inadequate soil conditions, such as low strength, high plasticity, and susceptibility to erosion, pose significant challenges to infrastructure development. These issues can lead to landslides, erosion, damage to structures, and increased maintenance costs. Soil stabilization helps maintain the integrity of slopes and embankments, protects surfaces from erosion, and improves soil resistance to weathering. Additionally, stabilization can mitigate the effects of expansive soils, reducing foundation movement and structural damage.

This study focuses on evaluating the performance of Solid Earth, a novel soil stabilization product, in enhancing soil properties. This research aims to comprehensively evaluate the performance of Solid Earth as a soil stabilization product. Specific objectives include determining optimal application rates for diverse soil types to maximize soil strength and durability improvements. Additionally, the study will assess the potential environmental implications of using Solid Earth and develop practical guidelines for its implementation in various soil stabilization projects. By achieving these objectives, this research seeks to contribute to the advancement of soil stabilization practices and inform effective decision-making in infrastructure development.

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The Importance of Soil Stabilization

Soil stabilization is a critical engineering practice that offers a multitude of benefits for both environmental sustainability and project success. By enhancing soil properties, stabilization plays a pivotal role in fostering sustainable environmental practices, minimizing dust generation and air pollution, and reducing soil erosion and sediment runoff. Moreover, it enables the utilization of marginal soils, expanding project possibilities while conserving prime agricultural land. The versatile application of soil stabilization extends beyond environmental benefits. It is adaptable to various projects, from construction to landscaping, enhancing soil strength and durability, and ultimately increasing load-bearing capacity and reducing deformation and settlement. This leads to improved resistance to erosion and weathering, ensuring the long-term performance and stability of infrastructure.

Beyond its technical advantages, soil stabilization is a cost-effective and sustainable solution. By utilizing locally sourced materials, reducing long-term maintenance expenses, and preserving natural resources, it aligns with sustainable development principles. Additionally, soil stabilization contributes to slope stability, surface protection, and mitigating the challenges posed by expansive soils, making it a comprehensive approach to soil management.

Furthermore, pavements constructed on non-stabilized bases often exhibit shorter lifespans and require more frequent maintenance. These bases are susceptible to water infiltration, leading to issues such as frost heave, potholes, and structural deterioration. Consequently, pavements built on non-stabilized bases often necessitate costly repairs and replacements.

In contrast, pavements with stabilized bases demonstrate superior performance and durability. The stabilization process enhances the soil's strength and resistance to environmental factors, resulting in a more resilient base. This translates to improved load-bearing capacity, reduced susceptibility to water infiltration, and a smoother driving surface.
As a result, pavements built on stabilized bases typically require less maintenance and have a longer lifespan, ultimately leading to significant cost savings over time.

By addressing these critical areas, soil stabilization leads to a sustainable and resilient infrastructure development.

Types of Soil Stabilizers

A variety of soil stabilizers are available, each with its own set of properties and applications. From the use of lime and fly ash to the integration of natural fibers, traditional methods, while effective in their prime time, come with a set of constraints. Their susceptibility to wear over time, coupled with environmental concerns, poses questions on their long-term viability. **Table 1** shows the most prominent soil stabilizers available in the construction industry. While lime and cement have been traditionally used for soil stabilization, their environmental impacts have prompted the exploration of alternative methods.

Lime, produced through the calcination of limestone, contributes to greenhouse gas emissions primarily through the release of carbon dioxide. Beyond its carbon footprint, lime can also have ecological implications. By increasing soil pH, it can disrupt the delicate balance of soil microbiota, potentially leading to reduced biodiversity and impaired soil health. Additionally, excessive lime application can result in leaching into nearby water bodies, altering their pH levels and adversely affecting aquatic ecosystems (Tiina, 2022).

As for cement production, it is a major contributor to global greenhouse gas emissions. The energy-intensive process of clinker production, which involves the calcination of limestone and clay, releases significant amounts of carbon dioxide. Furthermore, the extraction of raw materials for cement production can lead to environmental degradation. Cement manufacturing also consumes substantial energy, often derived from fossil fuels, exacerbating the industry's carbon footprint. The production process generates waste materials, such as kiln dust, which require proper management to prevent environmental contamination (Cheng et al., 2023; *Environmental Impacts of Concrete Construction and Manufacturing, 2023; Kilns, Calcination & Energy Efficiency, 2022*).

Based on those limitations, there is a need to evaluate a soil stabilizer that delivers the same benefits, while considering the environmental aspects of associated.

Table 1
Typical Soil Stabilizers Comparison

Method	Description	Performance Criteria	Constrains
Lime	Mixing lime with soil to improve its properties	Increased soil strength and load-bearing capacity. Reduced soil plasticity. Improved soil workability and frost resistance	Effectiveness depends on soil type, especially clays with higher plasticity Requires proper lime content based on soil characteristics Requires appropriate curing time for optimal results
Fly Ash	Mixing fly ash with soil to enhance its structural properties	Boosted soil stiffness. Increased resistance to erosion. Reduced soil shrink- swell potential. Improved soil drainage	Efficiency varies with the quality and type of fly ash Potential for leaching of heavy metals if not properly treated The mix proportions should be optimized for soil type
Cement-based stabilizers	Stabilization using Ordinary Portland Cement	Enhanced compressive strength. Increased secant modulus	Production processes are energy-intensive

Solid Earth: A Novel Soil Stabilization Solution

Solid Earth (SEi), a liquid polymer soil stabilizer developed by Solid Earth Inc is. an eco- friendly solution for enhancing soil properties, offering several advantages over traditional methods.

Such benefits include the following:

- Enhanced soil strength and durability, creating a robust surface capable of withstanding heavy loads.
- Reduced dust generation, especially in arid environments, protecting against wind erosion.
- Improved resistance to moisture and erosion
- Environmentally friendly formulation, maintaining the natural look of the soil.

At its core, Solid Earth is a polymer-water based solution. This means it harnesses the power of polymers large molecules made up of repeating subunits to bind and strengthen soil particles. The distinct advantage of such a composition is the ability to control the ratio of polymer to water, allowing for customization based on the desired strength of the stabilized material. When applied to soil, the polymer particles in the emulsion interact with soil particles to form a cohesive matrix. These polymers, typically elastomeric or thermoplastic water-based polymers, create a continuous film upon water evaporation that further binds soil particles together. This improves the soil's resistance to erosion and wear. While effective in stabilizing granular soils, the efficacy of polymer emulsions on fine- grained soils can vary (Tan et al., 2020).

In terms of installation process, a simple dilution with water and mixing with natural soil is recommended. Spraying the solution on the surface, followed by rolled compaction is suggested for optimal performance. While the dilution ratio of water to Solid Earth depends on the application and type of soil, Solid Earth offers a cost-effective solution compared to traditional methods. By binding soil particles together, it creates a durable and water-resistant surface, effectively controlling dust and erosion. This will reduce maintenance costs due to improved soil performance with potentially lower material and labor costs. Furthermore, treated soils are expected to exhibit improved durability and resistance to environmental factors. For structural applications, a lower dilution rate is recommended, whereas for dust mitigation purposes, lower dilution is suggested. It is worth noting that Solid Earth stabilization doesn't require heat during the process and that stabilization falls under stabilization category where strength gain occurs through coating aggregate particles and adhesive bonding. Using Solid Earth has an advantage, enabling it to maintain the overall structure of the soil, even when exposed to moisture for extended periods. Moreover, it has demonstrated the ability to effectively control dust, especially in desert areas, which is a significant benefit for projects in arid regions.

In this report, the effectiveness, strength, durability and environmental impact of Solid Earth are evaluated on different soil types, where the optimum content leading to maximum compaction density are determined. Furthermore, a Material Safety Data Sheet (MSDS) (Appendix A) and a Technical Data Sheet (TDS) (Appendix B) were developed as part of the effort.

Methodology

In this section the procedures and methodologies implemented in this project will be detailed (Figure 1). Seven different soil types were characterized for Solid Earth stabilization. The Liquid Limit, Plastic Limit and Plasticity Index were determined, followed by the soil size distribution for each. The optimum particle size and Solid Earth content, compressive strength, durability and environmental impacts as well as wind erosion and permeability were evaluated for the different soils acquired. Two dilution ratios were assessed, 10:1 and 20:1 of water to Solid Earth parts. Finally, lime stabilization was tested for strength and durability to compare with Solid Earth stabilized soils.

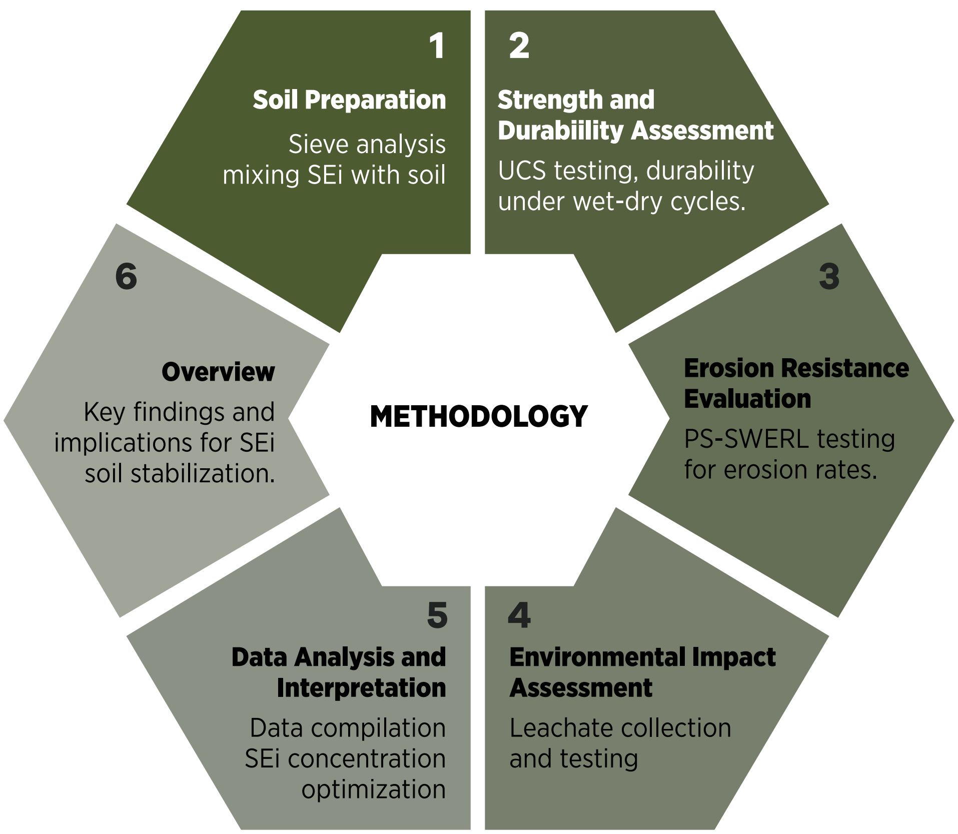


Figure 1
Methodology and Procedures

Materials and Soil Classification

Seven different soil types were evaluated in this project. Two soils were sourced from Arizona, and the other five were obtained from different locations in Barbados.

The first soil from Arizona called Crusher Fines (CF), is a very strong soil made from crushed gravel. It is made of sand with 10% fines. The second soil was sourced from Scottsdale, Arizona, and is made of sand with 2% fines. As for the five soils imported from Barbados, they were sourced from different locations across the island. These soils were labeled as "Botanical Garden (BG)", "White Hill (WH)", "Rayside (RS)", and "Lears (LS)". The last soil was originally made of asphalt pavement millings mixed with aggregates. In general, this soil is made of sand, asphalt millings and very little fines.

Liquid limit (LL), plastic limit (PL), and plasticity index (PI) are all parameters used to describe the properties of soil and clay and are also known as Atterberg limits (ASTM D4318, 2018):

- The Liquid Limit is the maximum amount of water a clay or silt can contain before it turns into mud and begins to flow. To determine the liquid limit, a soil sample is placed in a Casagrande cup, and a groove is made in the center. The sample is then jarred until the groove closes 12.7 mm (0.5 inches) after 25 blows. The liquid limit is the moisture content required to close the groove.
- As for the plastic limit, it is the minimum amount of water a soil can contain and still behave in a plastic manner, meaning it can be molded. To determine the plastic limit, a soil sample is repeatedly rolled into a thread until it crumbles. The plastic limit is the water content at which the thread crumbles.

The plasticity index (PI) of a soil is a numerical value that measures the range of moisture contents at which the soil deforms plastically. It is calculated (Equation 1) by subtracting the soil's liquid limit (LL) from its plastic limit (PL):

$$PI = LL - PL \quad \text{Equation 1}$$

The PI is expressed as a percentage of the soil sample's dry weight. It indicates the soil's fineness and its ability to change shape without changing volume. A high PI usually means the soil has a lot of clay or colloids, while a low PI usually means the soil has more silt. A PI of zero means the soil is non-plastic and has little to no silt or clay.

Based on the PI, the soil can be classified as follows:

- Non-plastic: PI = 0
- Slightly plastic: PI < 7
- Medium plastic: PI = 7–17
- Highly plastic: PI > 17

Furthermore, the soils were tested for Grain Size Distribution (ASTM D6913, 2017). This method was used to identify the best aggregate size that will yield larger thicknesses of stabilized soils. The results are shown in Figure 2 include, where all the soils evaluated in this project were sieved using a stack of sieve from ½'' to #200. The soil was handled as per field conditions and dried before sieving to obtain repeatable and consistent results compatible with the field observations.

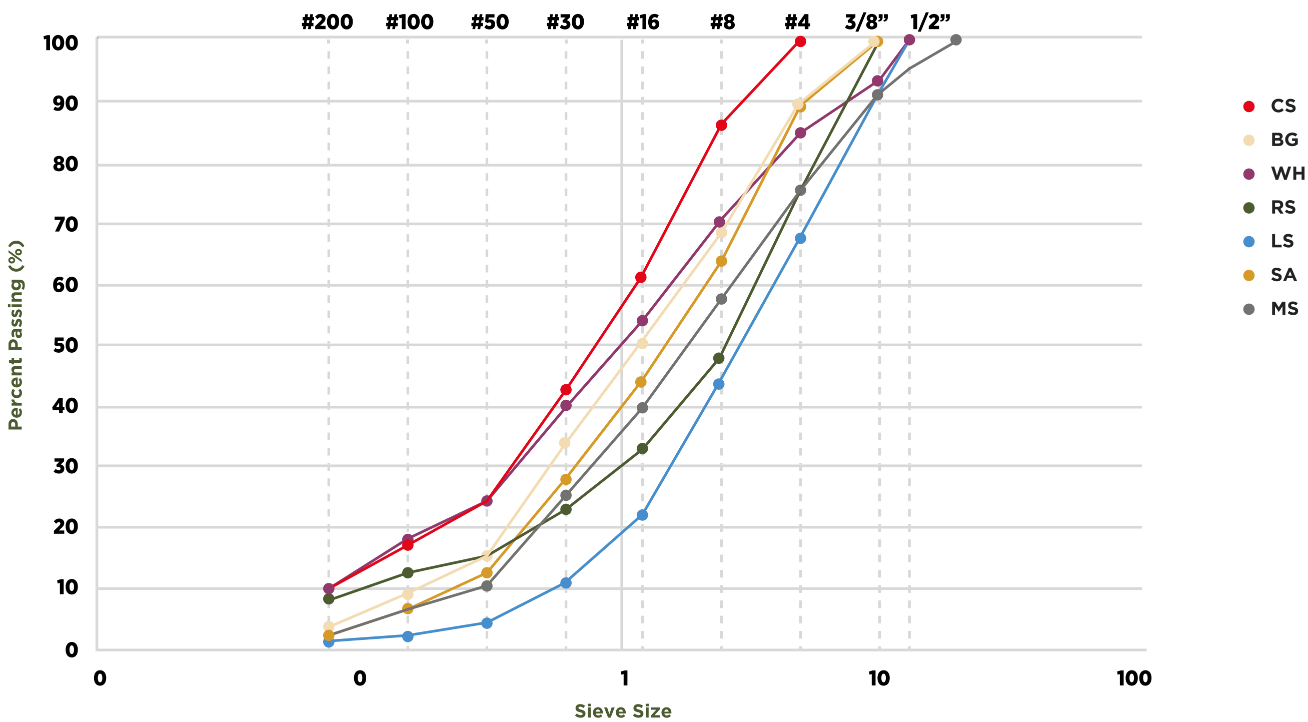


Figure 2
Soil Size Distribution

The Atterberg Limits of BG, WH and LS were tested in the laboratory, and are summarized in Table 2. The other soils were observed to have a granular behavior, where those parameters could not be tested. According to the Unified Soil Classification Standard (USCS) (Howard, 1986), the soils were classified as containing sands, silts and clays, where the White Hill soil is highly plastic, and Leans and Botanical Garden have medium plasticity.

PROPERTY	WH	LS	BG
LL	89%	54%	48%
PL	70%	45%	38%
PI	18%	9%	10%
USCS Soil Classification	Highly Plastic	Medium	Medium
	MH&OH	ML&OL	ML&OL
	Inorganic Silts sand and clay	Sandy Silts with clay	Sandy Silts with clay

Table 2
Liquid Limit, Plastic Limit and Plasticity Index of Barbados Soils

After multiple trials and errors, it was determined that the optimum aggregate size for sample stabilization of thicknesses less or equal to 100 mm (or 4 inches), aggregates passing sieve #4 showed the best results. If thinner thicknesses are desired, larger aggregate sizes could be used.

A visual representation of the soils tested in this study are shown in Figure 3.

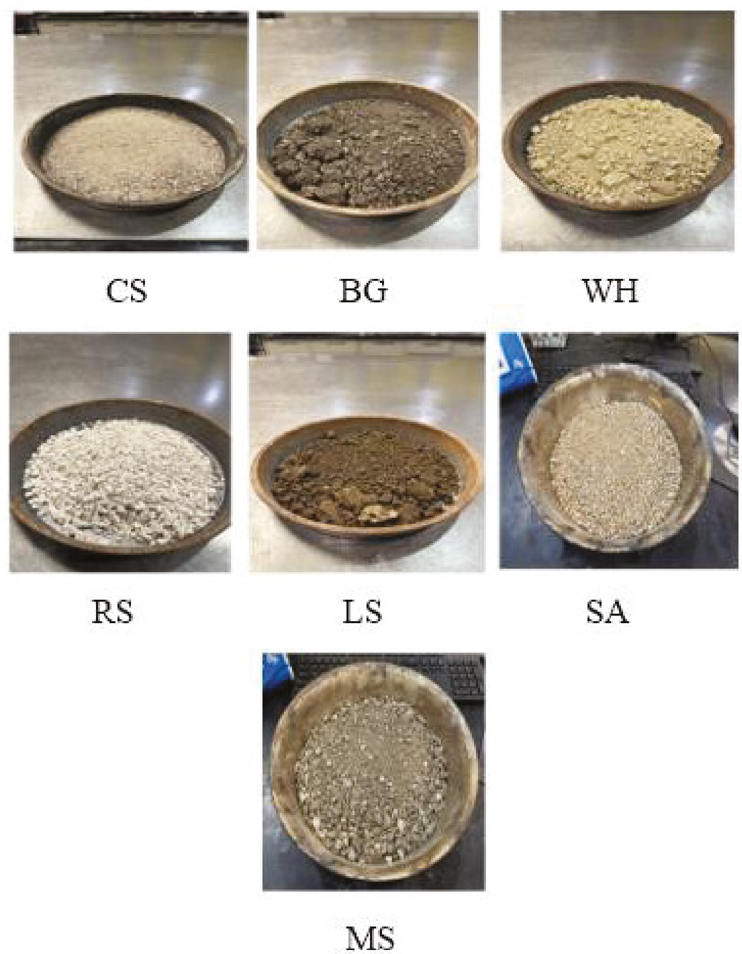


Figure 3
Visual Representation of the Soils Evaluated

Lime Stabilization

In order to compare the performance of the Solid Earth Stabilizer, a very commonly used stabilizer, Lime, was also tested for the same protocol. The soil used for lime stabilization was the Scottsdale soil. The lime content of the soil was determined according to ASTM D6276 (ASTM D6276, 2019). In this process, different percentages of lime are added to the soil while measuring the pH. A pH equivalent to 12.4 corresponds to the lime content that should be added to the soil. The results showed that for the Scottsdale soil, 2% lime content was recommended. The same

curing methods were adopted for the lime treated soil to compare performance with the Solid Earth treated soils.

Modified Proctor Test: ASTM D1557

This modified proctor test (ASTM D1557-21, 2021) was used to identify the optimum Solid Earth content to achieve maximum compaction in the field. This procedure is vital for testing as it will inevitably allow us to determine the proper amount of SEi content needed for the soils to achieve maximum performance when put in the field. Furthermore, it will give a direct indication of how much product needs to be implemented in field conditions, providing better control on cost and quantities needed for specific projects. Depending on the application type and the ratio, this test will allow the client and manufacturer to quantify how much product is needed to achieve optimum performance in terms of durability and strength. As this test is typically performed with water, compacting at water contents higher than the optimum water content results in a relatively dispersed soil structure that is weaker, more ductile, less pervious, softer, more susceptible to shrinking, and less susceptible to swelling than soil compacted dry of optimum to the same density. The soil compacted lower than the optimum water content typically results in a flocculated soil structure that has the opposite characteristics of the soil compacted wet of the optimum water content to the same density. The same analysis was followed with using SEi instead.

The following procedure was followed for all soils for the ratios of 10:1 and 20:1, and the apparatus used is shown in Figure 4.

- The soil was oven dried for at least 6 hours at 70oC prior to testing. The weight and dimensions of the empty mold were recorded, and about 1.36 kg (3-lbs) of soil were used every time.
- Several SEi contents were tested, ranging from 4% to 20% by weight of the dry soil. The modified soil was compacted in three layers using a 2kg (4.5-lbs) rammer with 25 uniform drops per layer. The compacted soil extended slightly above the mold's collar (extension) and was trimmed carefully.
- The weight of the mold filled with the soil was determined, and the moisture content of the soil was determined afterwards to confirm the amount of water initially added.

The moisture content versus dry compacted density was determined based on the obtained results for each soil type. The maximum dry compacted density was determined based on the graph, and the corresponding SEi content was recorded. The tests were carried out using both SEi and Moisture for comparison.

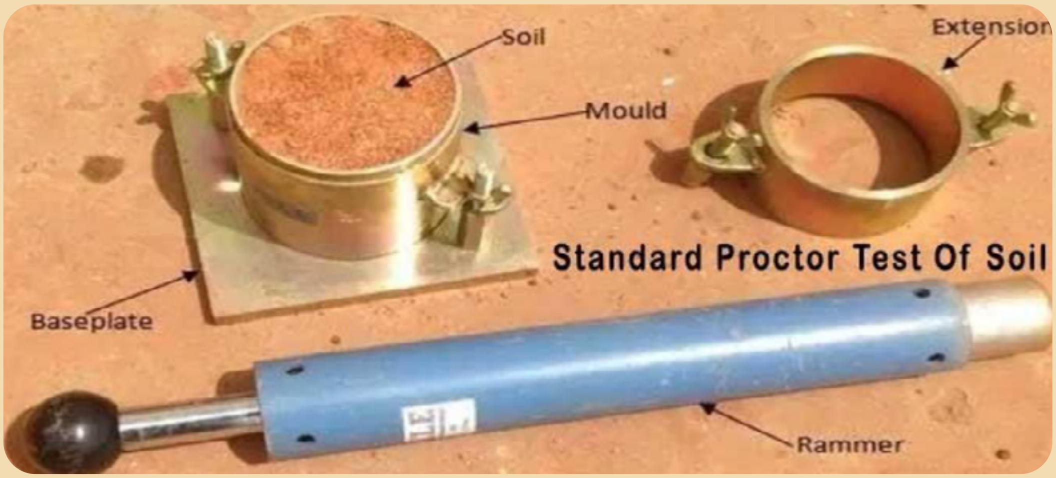


Figure 4
Modified Standard Proctor Test Apparatus

The obtained results are summarized in Table 3 for all soil types. When the SEi solution is used, an additional 1% was noted when compared to regular water.

SOIL TYPE	OPT. WATER CONTENT	OPT. SEi CONTENT
CF	11%	12%
BG	7%	8%
WH	7%	8%
RS	10%	11%
LS	12%	13%
SA	11%	12%
MS	9%	10%

Table 3
Optimum Water and SEi Contents for Ratios 20:1

For the 10:1 ratio, the modified proctor test was performed on the crusher fines soil. The results showed an optimum content of 10% of SEi compared to 12% with a ratio of 20:1. In other words, less solution is needed when the dilution ratio is smaller.

Unconfined Compression Strength Test (UCS): ASTM 2166

The unconfined compression strength (UCS) (ASTM D2166, 2010) test is essential in geotechnical engineering because it measures the compressive strength of soil samples without any lateral confinement. This test provides essential information about how much load the soil can bear before failure occurs, which is crucial for understanding the soil's bearing capacity.

This knowledge directly impacts the design and safety of construction projects, such as foundations, embankments, and other structures. Accurate UCS values help engineers ensure that their designs are capable of withstanding expected loads and environmental conditions, thus preventing potential structural failures.

When it comes to stabilized soils, the UCS test is invaluable for assessing the effectiveness of the stabilization methods. By evaluating the UCS of stabilized soils, engineers can verify that

the stabilization techniques are producing the desired improvements in soil performance, which is crucial for applications like road pavements and embankments.

In addition to design and effectiveness evaluation, the UCS test plays a critical role in quality control. For stabilized soils, it helps confirm that the treatment has been applied correctly and that the soil meets the required specifications for the project. For non-stabilized soils, it serves to ensure that the natural soil is adequate for its intended use, providing a benchmark for its strength and performance. In other words, UCS samples were created having a diameter of 30 mm (1.2 inches) and height of 75mm (3 inches) for a Height to Diameter Ratio of 2.5. A total of 6 replicates per soil type. Figure 4Figure 5 shows the apparatus used to test for compression under a constant strain rate of 1.2%.

In order to compare the performance of the stabilized soils, control samples were created using water at the optimum water content found in Table 3, whereas SEi stabilized samples were also created using the optimum SEi content found in the same table. Figure 6- UCS Test SamplesFigure 6 shows the final samples created before being tested.

Figure 5
UCS Testing Equipment

Figure 6
UCS Test Samples

Curing Time and Methods

An important observation was made during the creation of the samples concerning the proper curing mechanism. An initial attempt was to put the compacted specimens in the oven at a temperature of 70oC for a duration of 6 hours. Another attempt was to leave the uncured sample under a 250W heat lamp for a certain duration. After monitoring the samples under the lamp, it was found that the samples completely cured after 4 hours (Figure 7).

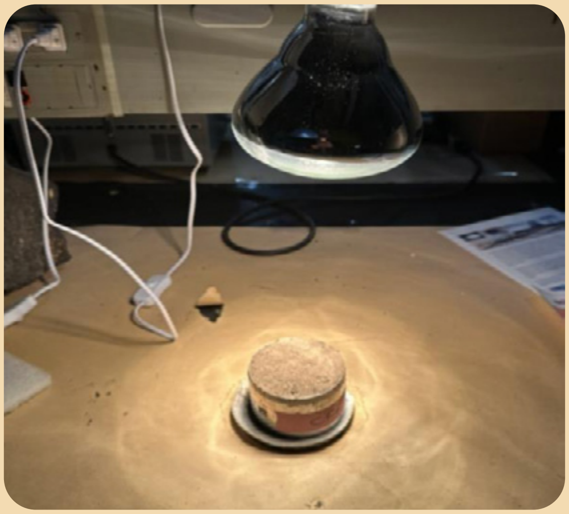


Figure 7
Sample Curing under Heat Lamp

These observations were made using the Crusher fines soils, as they were readily available in the laboratory in an abundant quantity, given the other soils were imported internationally and in a lower quantity.

Both cured samples (from the oven and heat lamp) were tested under the UCS testing machine at a strain rate of 1.2%/min. The results are summarized in Table 4 where it was clearly seen that under the lamp, the sample was curing more efficiently, reaching almost 60% more compression strength. Those observations led to the conclusion that slower curing, achieved with the heat lamp, was more effective and showed better strength compared to the faster and more aggressive curing achieved by the conventional oven. Therefore, curing the samples by means of the heat lamp was followed for all the other samples and soils for the rest of the testing protocol in this study.

Soil Tested (Crusher Fines)	Oven-Dried UCS (kPa)	Heat Lamp Dried UCS (kPa)
Control	240	1,578
SEi	1,260	2,201

Table 4
Different Curing Methods for UCS Results

Finally, the unconfined compression strength test results for all the soils at a ratio of 20:1 are shown in Table 5. It can be seen that SEi increased the UCS of the soils significantly, no matter the soil type. For stronger soils to begin with such as Crusher Fines and the Scottsdale soil, the results are not as substantial compared to the others but are still significant. As for the White Hill soil, given that it is a very problematic soil with high plasticity, the addition of Solid Earth did not seem to provide any benefit.

The interesting results to be noted are with reference to the Milling Soil, with a 324% improvement in UCS. As this soil is a mix of asphalt millings, the strength resulting from the SEi stabilization is interestingly positive.

Furthermore, the Botanical Garden soil as well as the Lears soil, having clay in their composition, are positively enhanced with the presence of SEi as stabilizer.

UCS (kPa)			
SOIL TESTED	**CONTROL**	**SEI TREATED (20:1) AY OPTIMUM CONTENT**	**% INCREASE**
CS	1579	2206	40%
BG	133	229	72%
WH	249	174	-30%
RS	285	1786	527%
LS	52	119	129%
SA	706	1256	78%
MS	143	608	324%

Table 5
UCS Test Results

With a dilution ratio of 10:1 for the crusher fines, the UCS was found to be equal to 2,639 kPa, leading to an increase in UCS of 67%, compared to 40% with a ratio of 20:1. This refers to a higher compression strength when using a lower dilution ratio.

For the lime-treated Scottsdale soil, the unconfined compression strength was found to be 327 kPa, which is not very promising in terms of strength compared to the control of 706 kPa.

In this test, the samples were failing in the form of tensile cracking. As the soil sample is compressed, it can develop cracks due to tensile stresses that arise from the applied compressive force. Tensile cracking often occurs when the soil's ability to withstand compressive stress is exceeded, causing cracks to form and propagate through the specimen. These cracks typically initiate at the sample's surface or from internal weaknesses. Figure 8 shows an example of this failure experienced in the laboratory during testing.

Figure 8
Tensile Failure Mode under UCS

Tensile Strength Ratio (TSR): AASHTO T283

The Tensile Strength Ratio (TSR) test, specified in AASHTO T283 (AASHTO T283, 2022), is a key procedure used to evaluate the moisture susceptibility of asphalt mixtures. This test helps in determining how the strength of an asphalt mixture changes when it is exposed to moisture, which is critical for assessing the durability and performance of asphalt pavements. Specifically, it evaluates the potential for moisture-induced damage, which can lead to issues such as stripping (the loss of asphalt binder from the aggregate surface) and reduced pavement durability.

In the case of the SEi stabilized soils, this test method was adopted to identify the effect of moisture as well as freeze and thaw on the stabilized soils, which are critical in wet-freeze regions.

To simulate the effects of moisture, the samples were divided into two groups: unconditioned, where the samples are tested without any moisture treatment, and conditioned, where they will undergo a moisture conditioning process. This involves submersion in water followed by freezing and thawing cycles, to simulate the impact of moisture on the sample.

The soil samples, made of crusher fines, were stabilized at their optimum SEi content and cured under the heat lamp. The samples were created using the standard proctor mold and trimmed to a thickness of 63.5mm. One sample was left on the side as the unconditioned, whereas the second sample was treated as follows:

- **As an initial step,** the specific gravity of the loose soil, treated with Solid Earth at optimum content as obtained in a similar way to the Maximum Theoretical Specific Gravity (Gmm), of asphalt mixtures (ASTM 2041).
- **Second,** the Bulk Specific Gravity (Gmb) of the cylindrical sample was obtained (ASTM 2726).
- **Based on the two values** obtained above for the sample to be tested, the air void content was found.
- **Based on the volume of the sample, saturating** the air voids by 80% was targeted by using a vacuum mechanical shaker for 5 seconds. A degree of saturation of 80% was necessary to ensure that the sample would be freezing without any damage.
- **The next step** includes wrapping the samples, both unconditioned and conditioned, and freezing them at a temperature of -18oC for 16 hours.
- **The next step** is to thaw the samples in a water bath at 60oC for 24hours.

Figure 9
TSR Testing Equipment

The test consists of loading the samples in the diametrical direction, at a rate of 50mm/min (2 in/min) at a temperature of 25oC, as shown in Figure 9.

However, after conditioning, the samples were still wet. An observation was made with regard to the testing conditions of the conditioned samples: fully wet, half dried (after leaving them to dry for a few hours) or fully dried (after moisture, freezing and thawing).

The strength of all the samples listed above are shown in Table 6 below. The TSR calculated was the ratio between the wet strength to the dry strength obtained after failure (Figure 10).

TESTING CONDITIONS	WET STRENGTH (kPa)	DRY STRENGTH (kPa) T	SR
Half Dry	78.5	266.4	29%
Fully Dry	192.1	194.6	99%
Fully Wet	9.41	194.5	5%

Table 6
TSR Test Results

It can be seen from the results that the strength of the soil sample stabilized with SEi was building up as the sample was drying. In other words, the completely wet sample had relatively no strength at all, whereas the strength increased from the half dry to the full dry condition. This mechanism reflects on self-healing properties, meaning that the soils stabilized with Solid Earth will maintain their properties as they dry up in the field.

A TSR value of 0.80 (or 80%) is generally considered acceptable, indicating that the tensile strength of the conditioned sample is at least 80% of the tensile strength of the unconditioned sample. This threshold helps ensure that the sample has adequate resistance to moisture-induced damage.

Figure 10
TSR Sample Failure

Durability Testing and Resistance by Wetting and Drying: ASTM D559

This test is a standard test method for measuring the durability of soil-cement mixtures (ASTM D559, 2023). The test evaluates the ability of soil-cement mixtures to resist disintegration, erosion, and other forms of physical degradation when subjected to cycles of wetting and drying. It aims to assess the durability of soil-cement mixtures by simulating the effects of natural environmental conditions, such as seasonal wetting and drying. In this project, the cement was replaced by the SEi stabilization, and the durability of the stabilized samples was evaluated by following the process below:

- Two samples were prepared at optimum SEi content, using the standard proctor mold and were cured under the heat lamp overnight. The longer curing time was due to the larger dimensions of the samples and to ensure that they were completely cured (Figure 11).
- The specimens underwent a series of wetting and drying cycles: each cycle typically includes 5 hours of immersion in water followed by 42 hours of drying in an oven at 71°C (160°F). a total of 12 cycles.
- After each cycle, the specimens are visually inspected for signs of cracking, scaling, or other damage. One sample remains untouched, while the other (Sample 2) is brushed using a wire brush a total of 18 times according to the standard.
- The weight of the specimens is recorded before and after each cycle to determine the amount of material lost due to disintegration.
- The dimensions of the samples after each wetting and drying cycle were also measured for possible volume change.
- Durability is determined based on the percentage of weight loss after a specified number of wetting and drying cycles. The lower the weight loss, the higher the durability of the soil-cement mixture.

Figure 11
Durability Test Samples

It was noted that after testing 6 cycles, the results were not significantly different. For this reason, only the first 6 cycles are reported for the following tested soils:

Table 7
Durability Test Results: Volume Change

VOLUME CHANGE		
SOIL TYPE	SAMPLE 1	SAMPLE 2
CF	1%	3%
RS	12%	8%
SA	-1%	-7%
MS	1%	-3%
CF LIME TREATED SOIL	-4%	-18%

Table 8
Durability Test Results: Weight Change

WEIGHT CHANGE		
SOIL TYPE	SAMPLE 1	SAMPLE 2
CF	-1%	-2%
RS	-1%	-1%
SA	-4%	-9%
MS	-1%	-2%
CF LIME TREATED SOIL	-2%-	4%

Based on the results, it can be clearly seen that the lime treated soil experienced the most shrinkage after 6 cycles compared to all the other SEi stabilized soils. As for the weight loss, all tested specimens were shown to be extremely durable, with a weight loss of less than 5% for the unbrushed sample, and less than 10% for the brushed one. Furthermore, according to the Portland Cement Association (PCA), a weight loss of less than 14% is considered to be acceptable. In this case, all the tested specimens showed very promising results. Similarly, the consistent volume change with the SEi stabilized samples indicates a good dimensional stability when compared to the lime stabilized soil.

As this test was to be performed on the other soil types, the Botanical Garden soil as well as White Hill and Lears soil were attempted. However, due to the clayey nature of the soil, the shrinkage associated with the clay while curing led to the failure of the samples as seen in the Figure 12 and Figure 13 below:

Figure 12
Lears Durability Sample

Figure 13
White Hill and Botanical Garden Durability Samples

Based on those observations, it was determined that the Solid Earth stabilization is still effective for clayey and silty soils in terms of erosion control but is less effective for strength purposes to some extent. For thinner layers, the stabilization may still work based on the clayey and sand content of the soil, as the shrink-swell behavior was still minimized. For best performance, mixing sand with clayey soils may minimize this effect even further.

Environmental Impact: Leachate Analysis

Nutrients Analysis

The leachate analysis helps determine the potential for contamination of groundwater and surface water by identifying harmful chemicals present in the leachate. Nutrients in leachate are key indicators of the potential environmental impact on surrounding ecosystems, particularly water bodies.

- **Presence of Ammonia (NH3):**

Ammonia in leachate primarily originates from the decomposition of organic matter, particularly proteins and urea in waste materials (Burton & Watson-Craik, 1998). High concentrations of ammonia can be toxic to aquatic life, causing oxygen depletion in water bodies and contributing to eutrophication. Ammonia is also a precursor to nitrate through the process of nitrification. The presence of Ammonia in high levels causes toxic buildup in tissues and blood.

- **Presence of Nitrate (NO3-):**

Nitrate (Follet, 2012) is formed from the oxidation of ammonia during nitrification, a process facilitated by bacteria. Nitrate is highly soluble and can easily contaminate groundwater. Excessive nitrate in water can lead to eutrophication, causing algal blooms, and depleting oxygen levels, which harm aquatic ecosystems. In drinking water, high nitrate levels can cause methemoglobinemia, or "blue baby syndrome," in infants. Nitrite and Nitrate at high levels increase heart rate, nausea and headaches.

- **Presence of Phosphate (PO43-):**

Phosphates are less mobile than nitrates but can still leach into groundwater under certain conditions. They are a primary nutrient that can cause eutrophication in freshwater systems. When phosphate levels are high, they can promote excessive growth of algae and aquatic plants, leading to oxygen depletion, fish kills, and the disruption of aquatic ecosystems.
Monitoring the levels of ammonia, nitrate, and phosphate in leachate is therefore essential to prevent such ecological impacts and protect water quality (Correll, 1998).

- **Presence of Chlorine (Cl-):**

The presence of chlorine, primarily as chloride (Boyd, 2020), in leachate is an important consideration due to its environmental impact, challenges in treatment, and potential for regulatory non-compliance. While chloride is generally less reactive than many other contaminants, its presence in leachate can still have significant environmental and operational implications. High levels of chloride in leachate can be harmful to both terrestrial and aquatic environments. Chloride is highly soluble and can easily leach into groundwater, making it a common contaminant in water bodies near landfills or other waste disposal sites. Elevated chloride levels in surface water and groundwater can lead to increased salinity, which can adversely affect aquatic life, especially freshwater species that are sensitive to changes in salinity. In soil, high chloride concentrations can disrupt the nutrient balance, leading to reduced agricultural productivity and harm to plant life.

From an operational perspective, Chloride is difficult to remove using conventional leachate treatment methods such as biological treatment or filtration, which means high chloride levels might require additional or specialized treatment processes, like reverse osmosis or ion exchange, to reduce concentrations before discharge. Additionally, chloride can contribute to the corrosion of infrastructure, such as pipes and treatment equipment, particularly in the presence of other aggressive ions.

On the other hand, Dissolved Organic Carbon (DOC) and Dissolved Inorganic Carbon (DIC) (Schwarzenbach et al., 2002) are also important parameters in leachate analysis, as they provide insight into the carbon content and its impact on both the environment and the leachate treatment process. DOC refers to the organic molecules dissolved in water, primarily originating from the decomposition of organic matter, such as plant material, food waste, and other carbon- based substances. DOC is a key indicator of the organic load in leachate and plays a significant role in several environmental processes. High DOC levels can contribute to the formation of disinfection byproducts (DBPs) during water treatment, which are harmful to human health. Additionally, DOC can influence the mobility and bioavailability of heavy metals and other contaminants, as organic molecules can form complexes with these substances. In natural waters, elevated DOC levels can also promote microbial activity, leading to increased oxygen consumption and potential depletion of dissolved oxygen, further impacting aquatic ecosystems.

As for DIC (Stumm & Morgan, 1996), includes carbon species such as carbon dioxide (CO^2), bicarbonate (HCO^{3-}), and carbonate (CO_3^{2-}). DIC primarily arises from the dissolution of carbonates in waste materials, microbial respiration, and the breakdown of organic matter. The balance of DIC species is closely related to the pH of the leachate, with higher pH levels favoring the presence of bicarbonate and carbonate, and lower pH levels favoring carbon dioxide. DIC plays a crucial role in buffering the leachate, helping to stabilize its pH and mitigate the corrosive effects of acidic conditions. Overall, both DOC and DIC are vital for understanding the carbon dynamics within leachate. Monitoring DOC helps assess the potential for organic contamination and its impact on water treatment and ecosystems. High DOC levels may require additional treatment processes to remove organic carbon before discharge. On the other hand, DIC is crucial for understanding the leachate's buffering capacity and its potential effects on downstream water chemistry. Together, DOC and DIC provide a comprehensive view of the carbon content in leachate, informing both environmental impact assessments and the design of appropriate treatment systems.

In order to test for all those nutrients, stabilized samples with Solid Earth for both ratios 10:1 and 20:1 were soaked in a jar full of distilled water for 1 month prior to being tested. A water sample from the jar was sent to the laboratory for testing along with a sample of distilled water for comparison. The results along with the acceptable levels are shown below in Table 9:

Table 9
Leachate Analysis - Nutrients

NUTRIENTS	CONTROL (mg/L)	10:1 (mg/L)	20:1 (mg/L)	ACCEPTABLE LEVELS
C1-	0.197	30.183	44.9	Maximum safe level in drinking water: 250 mg/L (2019)
3-	0.002	0.072	0.026	Maximum safe level in rivers: 0.1 mg/L (2011)
NH4	ND	1.19	ND	Ammonia Range for safe level in water: 0.25 mg/L to 32.5 mg/L (2017) Maximum safe levels of Nitrite and Nitrate: 1 mg/L and 10 mg/L respectively (2017)
NO2	0.0005	0.0058	0.0024	
NO2+NO3	0.004	0.057	0.011	
DIC	6.087	56.96	37.53	In most surface water 3.5 to 350ppm (Cole et al., 2021)
DOC	0.8272	36.18	50.99	Surface waters typically show thousands of mg/L depending on the source (Chapelle, 2022)

According to the Table 9, all stabilized samples, with both ratios, are within the safe levels for the nutrients when it comes to surface and drinking waters. For the lower dilution ratio (10:1), where the solution is more concentrated, higher concentrations are observed but still within the acceptable ranges.

Metal Concentrations

Metals in leachate are crucial to analyze due to their potential toxicity, mobility, and long- term environmental impact. The specific metals that are commonly analyzed in leachate include both heavy metals and trace metals, which can originate from various sources in the waste stream. The presence of these metals in leachate is a significant concern due to their toxicity, potential for bioaccumulation, and persistence in the environment. Monitoring and analyzing these metals are essential for assessing the potential risks to human health, groundwater, surface water, and ecosystems.

While a lot of metals are worth analyzing, only the concentrations that are higher compared to the control distilled water are presented in this report along with the acceptable level in Table 10:

Table 10
Leachate Analysis- Metals

METALS	CONTROL (mg/L)	10:1 (mg/L)	20:1 (mg/L)	ACCEPTABLE LEVELS (MERIDE & AVENEW, 2026)
Ca (Calcium)	0.51	60.25	43.31	In water, high levels can contribute to water hardness and may affect industrial processes and water distribution systems. In soil, excessively high levels can interfere with the uptake of other essential nutrients by plants. Permissible levels: 75 mg/L
K (Potassium)	1.09	4.43	7.33	Not a concern as a pollutant Permissible levels: 12 mg/L
Mg (Magnesium)	0.31	6.78	5.99	Major contributor to water hardness, along with calcium. In water, high levels can contribute to soil salinity and affect plant growth. May need to consider the content in irrigation water to prevent soil degradation. Permissible levels: 50 mg/L
Na (Sodium)	2.1	55.89	58.4	High levels contribute to high salinity. Permissible levels: 250 mg/L

According to the results noted in Table 10, the same conclusion can be made for the metal concentrations: the addition of Solid Earth is unharmful to the surface water, soil, and surrounding vegetations in case of rain. The metals presented in that table only reflect the ones that had a different concentration to distilled water. Given that other toxic metals are normally looked at in a leachate analysis (Such as Lead, Mercury, Cadmium, Arsenic, Chromium, Zinc, Copper...etc.), these metals had an equal concentration to the one of distilled water, which is considered to be unharmful to the environment as well.

Permeability Test (Ksat): ASTM D5084

It is important to understand the permeability of a stabilized soil to evaluate its potential for reducing water infiltration and enhancing the surface runoff control. The Ksat, which is saturated hydraulic conductivity, indicates the ease with which water moves through the soil. It is an essential parameter for understanding water infiltration, drainage, and the potential for surface runoff. For this reason, samples made of crusher fines were used to measure this parameter with and without Solid Earth as follows (ASTM D5084, 2016):

- Soil samples were prepared with and without Solid Earth treatment in standard 250 ml sample rings
- They were then saturated from below with degassed water for 24 hours to ensure complete saturation
- The saturated samples were then placed in the Ksat device (Figure 14), and a constant head of water was applied
- The volume of water passing through the soil sample was measured over time and the Ksat was calculated according to Darcy's Law:

$$K = \frac{\Delta Q \times L}{A \times \Delta h \times \Delta t}$$

Where k is the hydraulic conductivity (m/s), ΔQ is the flow for a given time Δt (m^3), L is the length of the specimen (m), A is the cross-sectional area of the specimen (m^2) and Δh is the average head loss across the permeameter (m).

The same procedure was also done on a control sample, that was not stabilized with Solid Earth. In comparison, the control crusher fines sample had a Ksat of 5.3E-6 m/s, compared to a Ksat of 8.5E-7 m/s for the stabilized sample. This showed that the sample stabilized with SEi had a high permeability resistance, meaning a low water infiltration. This can help control erosion. Since water does not easily infiltrate these soils, surface runoff is reduced, decreasing the likelihood of soil erosion caused by water flow. In addition, high permeability resistance can be advantageous for environmental protection. Such soils are effective in containing pollutants and preventing their migration into groundwater. This is particularly useful in constructing barriers or liners for landfills and containment systems for hazardous waste. This can also be useful in stormwater management, as well as construction and foundation stability.

However, it can also pose some challenges as proper drainage must be in place, as excess water may accumulate on the surface rather than infiltrating. Therefore, proper management and conditioning of high permeability resistance soils are essential to maximize their benefits.

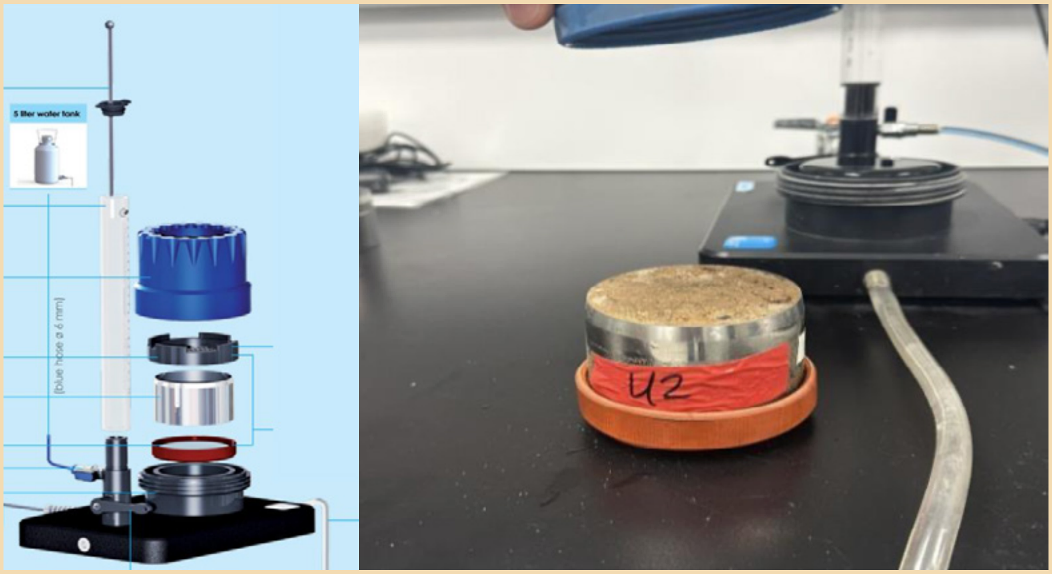


Figure 14
Hydraulic Conductivity Test Equipment and Sample

Wind Erosion Resistance Using the Portable In-Situ Wind Erosion Laboratory (PI- SWERL)

The PI-SWERL is an advanced instrument designed to provide real-time measurements of wind erosion and dust emissions. Its portability allows researchers to study these phenomena in a wide range of natural environments, from deserts to agricultural fields. It is equipped with a suite of sensors designed to capture comprehensive data on wind erosion (Stout, 2007). Key components include wind speed and direction sensors to measure the driving force of erosion, dust concentration sensors to quantify the number of suspended particles, soil moisture probes to assess the soil's susceptibility to erosion, and a data logger to store and record the collected data. These components work together to provide a detailed understanding of wind erosion processes in various environments.

More specifically, the core component of the PI-SWERL is a small, portable wind tunnel that creates controlled wind flow over the soil surface to mimic natural wind conditions. It consists of a circular chamber with a motorized fan that generates adjustable wind speeds. In addition, a set of sensors and instruments are integrated into the device to capture and analyze dust particles emitted from the soil during testing. The system measures the concentration, size, and composition of dust particles. It has a Rotating Annular Blade (RAB), that rotates at varying speeds, increasing the shear stress on the soil surface to simulate different wind conditions. This helps in assessing the threshold wind speed required to initiate particle movement. Finally, it is equipped with a computerized control system that allows researchers to set experimental parameters and monitor the tests in real time. Data collected during tests, such as wind speed, dust concentration, and particle size distribution, are recorded for analysis.

The testing methodology consists of preparing samples in a circular pan, stabilized with simply water and Solid Earth for comparison, left to cure following the same procedure throughout the project. After placing the sample underneath the foam seal (Figure 15), the PI-SWERL will assess the soil's resistance to wind erosion and dust emissions by measuring PM10 concentrations. PM10 refers to particulate matter (PM) with a diameter of 10 micrometers or less and was measured inside the chamber using a DustTrak II monitor at one second intervals. These particles are small enough to be inhaled into the lungs and can cause various health issues.

The rotating speed of the blade was then increased gradually from 0 to 6,000 RPM within 700 seconds (Figure 16).

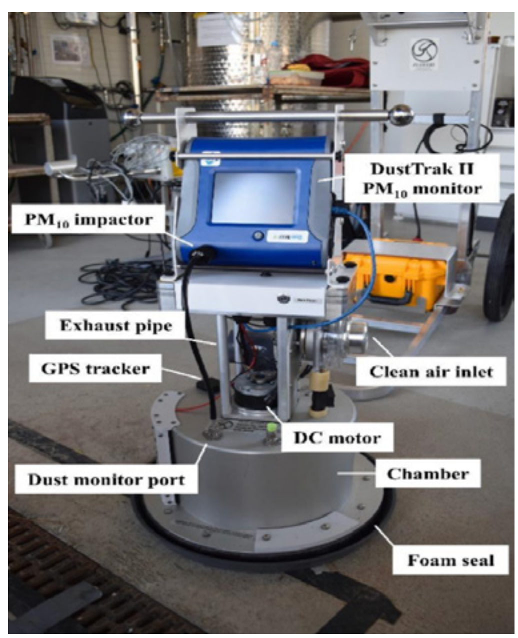
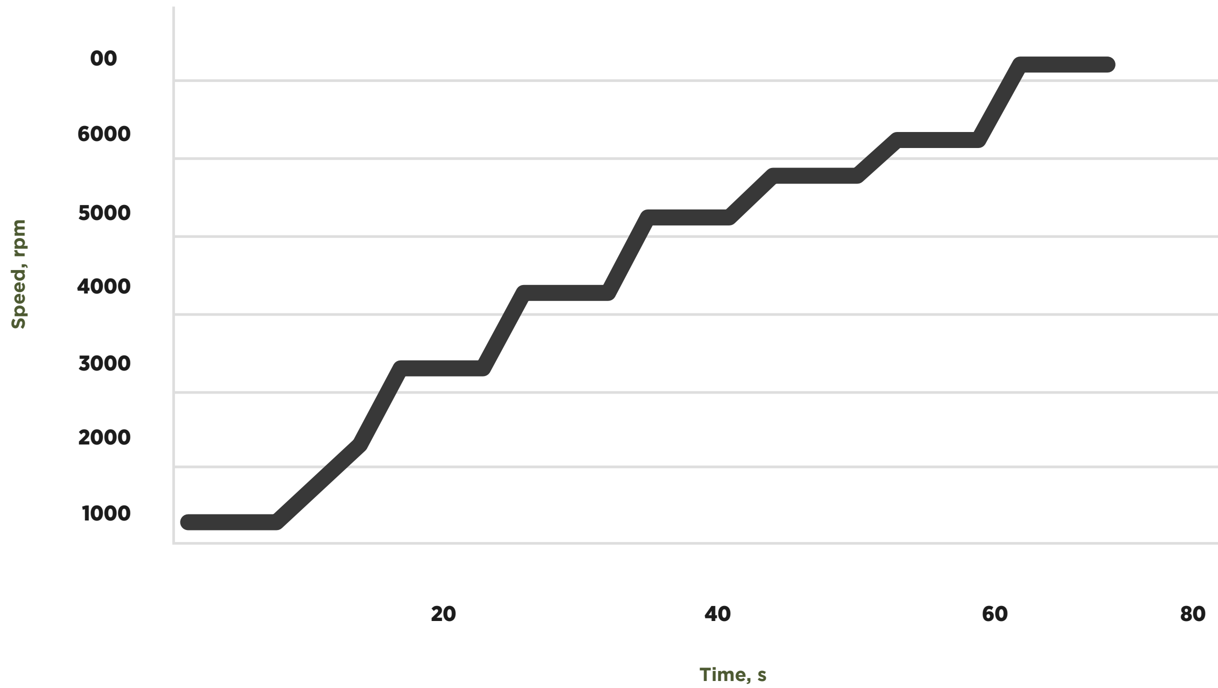


Figure 15
PI-SWERL Testing Equipment

Figure 16
Speed Increase with Time for PI-SWERL Testing



The PM10 concentrations for both samples were recorded with time. At 12 m/s (about 4000 RPM after 12 minutes), which is considered to be very high wind speed conditions (van Leeuwen et al., 2021), are presented in Table 11 below:

SOIL TYPE	CONTROL (mg/m3)	SEi (mg/m3)	REDUCTION %
CF	8.7	0.868	90%
RS	0.699	0.652	7%
WH	189	67	65%
LS	7.2	3.74	48%

Table 11
PI-SWERL Test PM10 Results

Based on the results observed in Table 11, it can be seen that the stabilization was very effective with respect to wind erosion resistance. A decrease in dust concentration up to 90% was measured. A smaller reduction in dust concentration was measured for the Rayside soil, as it has lower content of fines.

Summary and Conclusions

Soil stabilization enhances the physical properties of soil, improving its strength, durability, and resistance to erosion. It is commonly used for unpaved roads, parking lots, dust control in industrial and construction sites, and pathways. Additionally, it helps control erosion on slopes, reduces foundation movement in expansive soils, and increases the durability of pavements by making soil more resistant to environmental factors like frost and moisture. Overall, soil stabilization increases load-bearing capacity, reduces deformation, and minimizes dust generation, soil erosion, and sediment runoff.

Common stabilizers used in the industry are Cement and Lime. However, these stabilizers have potential for leaching, have energy-intensive productions and are associated with a large amount of CO2 emissions. Solid Earth (SEi), a soil stabilizer by Solid Earth Inc. is an eco-friendly innovative solution that binds soil particles together, creating a durable and water-resistant surface.

In this study, the effect of SEi on seven different soils was evaluated in terms of strength, durability, environmental impact, wind erosion and permeability. Test results were compared to a lime stabilized soil to quantify the performance. The modified proctor test was used to determine the optimum stabilizer content that will achieve a maximum compaction in the field, leading to an improved performance. Furthermore, two dilution ratios (10:1 and 20:1) were evaluated. As part of the study, it was found that a slower and steady curing method allowed the stabilizer to achieve a higher compression strength when compared to a fast curing by means of a conventional oven. A heat lamp was used to cure the samples, mimicking field conditions. According to the material characterization, it was found that Solid Earth works best with aggregates sandy soils passing sieve #4, to achieve soil thicknesses up to 100mm with little fines (<10%).

The Solid Earth stabilized soils exhibited an improved unconfined compression strength, regardless of the soil type except for the high plasticity soil. In terms of durability, the stabilizer exhibited excellent durability with minimal weight loss and volume change when compared to lime stabilized soils. The results of the environmental testing from the leachate analysis showed that it has minimal impact on groundwater contamination and surrounding vegetation, which enhances its environmentally friendly aspect. With respect to the wind erosion testing, it was shown that a reduction of dust by up to 90% was exhibited, reflecting on its impressive ability to resist erosion under high wind speed simulations. Finally, with respect to the soil permeability, the Solid Earth stabilized soils showed a decrease in water infiltration, promoting a better control over surface water runoff and pollutant migration into groundwater. Based on the obtained results, Solid Earth was found to be a promising soil stabilizer promoting strength, durability and environmental aspects when compared to other stabilizers in the market. It was found that it works best with sandy like materials in terms of both strength and erosion resistance: for strength purposes, using a higher ratio (10:1) will yield higher strength whereas for erosion and dust control, a ratio of 20:1 may be deemed sufficient. Furthermore, SEi was found to be effective to some extent for heavy clayey soils, whereas the swell-shrinkage effects were minimized but not eliminated. For this reason, those types of soils are recommended to be used with Solid Earth for erosion control purposes or mixed with a higher concentration of sand to offset the shrinking mechanism of the soil prior to stabilization. For sandy materials, the SEi stabilization was successful and effective on both strength and erosion levels.

References

AASHTO T283. (2022). *Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage.*

Agency for Toxic Substances and Disease Registry. (2017). *Case Studies in Environmental Medicine (CSEM) Nitrate/Nitrite Toxicity. U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry Division of Toxicology and Human Health Sciences.*

ASTM D559. (2023). *Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures.*

ASTM D1557-21. (2021). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 (2,700 kN-m/m3)).*

ASTM D2166. (2010). Standard Test Method for Unconfined Compressive Strength of Cohesive Soil.

ASTM D4318. (2018). *Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.*

ASTM International. *https://doi.org/10.1520/D4318-17*

ASTM D5084. (2016). *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.*

ASTM D6276. (2019). *Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization.*

ASTM D6913. (2017). *D6913 Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis. https://www.astm.org/d6913-04r09e01.html*

Boyd, C. E. (2020). *Water Quality: An Introduction. Springer International Publishing. https://doi.org/10.1007/978-3-030-23335-8*

Burton, S. A. Q., & Watson-Craik, I. A. (1998). *Ammonia and nitrogen fluxes in landfill sites: Applicability to sustainable landfilling. Waste Management & Research: The Journal for a Sustainable Circular Economy, 16(1), 41–53. https://doi.org/10.1177/0734242X9801600106*

Chapelle, F. H. (2022). *Dissolved Organic Carbon in Groundwater Systems.*

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). *Projecting future carbon emissions from cement production in developing countries. Nature Communications, 14(1), 8213. https://doi.org/10.1038/s41467-023-43660-x*

Cole, J. J., Hararuk, O., & Solomon, C. T. (2021). *Chapter 7 - The Carbon Cycle: With a Brief Introduction to Global Biogeochemistry. In K. C. Weathers, D. L. Strayer, & G. E. Likens (Eds.), Fundamentals of Ecosystem Science (Second Edition) (pp. 131–160). Academic Press. https://doi.org/10.1016/B978-0-12-812762-9.00007-1*

Correll, D. L. (1998). *The role of phosphorus in the eutrophication of receiving waters: A review. Journal of Environmental Quality, 27(2), 261–266.*

Department of Health, New York State. (2019). *Salt and Drinking Water. https://www.health.ny.gov/environmental/water/drinking/salt_drinkingwater.htm*

Environmental impacts of concrete construction and manufacturing. (2023). *https://www.converge.io/blog/environmental-impacts-of-concrete*

EnviroSci Inquiry. (2011). *Lehigh River Watershed Explorations. https://ei.lehigh.edu/envirosci/watershed/wq/wqbackground/phosphatesbg.html*

F**ollet, R. (2012).** *Nitrogen Management and Ground Water Protection. https://shop.elsevier.com/books/nitrogen-management-and-ground-water- protection/follett/978-0-444-87393-4*

Howard, A. K. (1986). *Soil classification handbook: Unified soil classification system. Second edition. Denver, Colo. : Geotechnical Branch, Division of Research and Laboratory Services, Engineering and Research Center, Bureau of Reclamation, 1986. https://search.library.wisc.edu/catalog/999656841702121*

Kilns, Calcination & Energy Efficiency. (2022). *Specify Concrete. https://www.specifyconcrete.org/blog/kilns-calcination-energy-efficiency*

Meride, Y., & Ayenew, B. (2016). *Drinking water quality assessment and its effects on residents health in Wondo genet campus, Ethiopia. Environmental Systems Research, 5(1), 1. https://doi.org/10.1186/s40068-016-0053-6*

Schwarzenbach, R. P., Gschwend, P. M., & Imboden, D. M. (2002). *Environmental Organic Chemistry (1st ed.). Wiley. https://doi.org/10.1002/0471649643*

Stout, J. E. (2007). *Simultaneous observations of the critical aeolian threshold of two surfaces.*

Geomorphology, 85(1), 3–16. *https://doi.org/10.1016/j.geomorph.2006.03.034*

Stumm, W., & Morgan, J. J. (1996). *Aquatic chemistry: Chemical equilibria and rates in natural waters (3rd ed). Wiley.*

Tan, E. H., Zahran, E. M. M., & Tan, S. J. (2020). *A review of chemical stabilisation in road construction. IOP Conference Series: Materials Science and Engineering, 943(1), 012005. https://doi.org/10.1088/1757-899X/943/1/012005*

Tiina. (2022, March 28). *Lime and CO2—What's the big deal? Nordkalk. https://www.nordkalk.com/lime-and-co2-whats-the-big-deal/*

Van Leeuwen, C. C. E., Fister, W., Vos, H. C., Cammeraat, L. H., & Kuhn, N. J. (2021). *A cross- comparison of threshold friction velocities for PM10 emissions between a traditional portable straight-line wind tunnel and PI-SWERL. Aeolian Research, 49, 100661. https://doi.org/10.1016/j.aeolia.2020.100661*

Appendix A

Final Report

Solid Earth Material Safety Data Sheet (MSDS)

Appendix A

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

GENERAL INFORMATION

PRODUCT NAME	SOLID EARTH®
General names	Soil Solidifier, Soil Stabilizer Dust Control Agent, Dust Inhibitor, Dust Retardant
Manufacturer	Solid Earth® https://www.solidearthinc.com/ 1027 E Curry Rd Tempe, AZ 85288, USA
Associated patents	U.S. Patent No. Pending
Contact	HADAR RAHAV - PRESIDENT hadar@solidearthinc.com Tel: 480.446.9000 Fax: 480.446.9001
Description	Solid Earth is a unique, innovative, eco-friendly liquid polymer soil solidifier installed using existing or imported soil producing durable, long-lasting, water resistant, solid load-bearing roadways, pathways and other solid high compressive strength surfaces. When used to stabilize existing soil on the ground, slopes or embankments, Solid Earth dramatically reduces mud, dust and erosion. Solid Earth surfaces provide exceptional durability and longevity without harming or polluting the environment while maintaining existing indigenous landscapes.

Appendix A

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

HAZARDS CLASSIFICATION

U.S.HAZARDOUS MATERIALS IDENTIFICATION SYSTEM (HMIS) RATING

Health	**0**	No significant risk to health
Flammability	**1**	Non-flammable, but will burn on extended contact to flame or high temperature.
Physical Hazard	**0**	Stable, non-explosive and non-reactive
Personal Protection	**-**	No special hazard in normal use

ACCORDING TO OSHA CRITERION, THIS MATERIAL IS NOT CONSIDERED HAZARDOUS.

Appearance	Viscous fluid, white color
Odor	Resinous-almond
Safety Hazards	Nonflammable, but will burn on extended contact to flame or high temperature.
Health Hazards	Harmful: may cause lung injury if swallowed and enters air ways
Environmental Hazards	Not classified as hazardous for the environment.

HEALTH HAZARDS

Inhalation	In usual conditions of use, this material is not likely to be a primary way of exposure
Skin contact	Repeated or prolonged or skin contact without appropriate cleaning can block the pores of the skin follow-on disorders such as acne.
Eye contact	May cause slight irritation
Ingestion	Harmful: may cause lung injury if swallowed and enters air ways

Signs and symptoms

Signs and symptoms, if material enters lungs, may include choking, wheezing, coughing, chest congestion, difficulty in breathing, shortness of breath, and/or fever. The beginning of respiratory symptoms may be postponed for some hours after contact. Ingestion may result in vomiting, diarrhea, and/or nausea.

Appendix A
SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

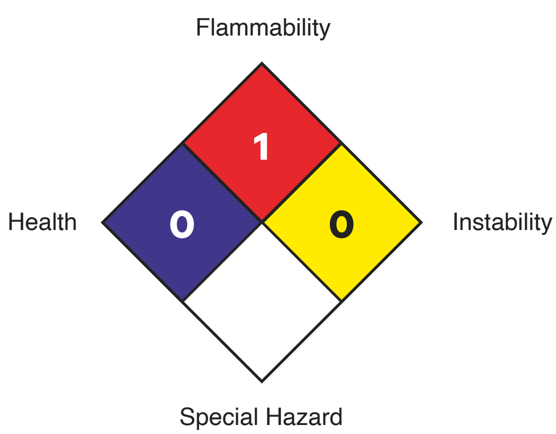
FIRE-FIGHTING MEASURES

Flammability	Non-flammable, but will burn on prolonged exposure to flame or high temperature.
Extinguishing media	Use foam, water spray or fog. Dry chemical powder, carbon dioxide, sand or earth may be used for small fires only.

SPECIAL FIRE FIGHTING PROCEDURES & PROTECTIVE EQUIPMENT

Do not use water in a jet. Proper protective equipment including breathing apparatus must be worn when approaching a fire in a confined space.

U.S. NATIONAL FIRE PROTECTION ASSOCIATION (NFPA) 704 HAZARD CLASS



Legend:

0 - Minimal
1 - Sligth
2 - Moderate
3 - Serious
4 - Severe

Appendix A

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

FIRST-AID MEASURES

INGESTION	No treatment necessary under normal conditions of use. If swallowed do not induce vomiting. If symptoms persist, request medical attention.
INHALATION	No treatment necessary under normal conditions of use. If breathing difficulties develop move injured party away from source of exposure and into fresh air in a position comfortable for breathing. If symptoms persist, look for medical attention.
SKIN CONTACT	No treatment necessary under normal conditions of use. Remove contaminated clothing. Wash affected area with mild soap and water. If irritation or redness develops and persists, seek medical attention.
EYE CONTACT	If irritation or redness develops from exposure, flush eyes with clean water. If irritation persists, ask for medical attention.

HANDLING AND STORAGE

STORAGE	Keep container tightly closed in a cool, well-ventilated place. Use properly labeled and closeable containers.
HANDLING	Avoid breathing vapors or mist. Avoid contact with eyes. Avoid prolonged or repeated contact with skin. Wash thoroughly after handling. When handling product in drums, safety footwear should be worn, and proper handling equipment should be used.

Appendix A
SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

ACCIDENTAL RELEASE MEASURES

PROTECTIVE MEASURES	Stop the leak, if possible. Avoid contact with skin and eyes. Use appropriate containment to avoid environmental contamination. Prevent from spread in go entering drains, ditches, sewers, rivers or open bodies of water by using sand, earth or other appropriate barriers.
CLEAN-UP METHODS	Avoid accidents, clean up immediately. Slippery when spilled. Prevent from spreading by making a barrier with sand, earth or other containment material. Reclaim liquid directly or in an absorbent. Soak up residue with an absorbent such as clay, sand or other suitable material and dispose of properly.
ADDITIONAL ADVICE	Local authorities should be advised if significant spillages can't be contained.

TOXICOLOGICAL INFORMATION

SKIN IRRITATION	Likely to be slightly irritating.
EYE IRRITATION	Likely to be slightly irritating
RESPIRATORY IRRITATION	Breathing of vapors or mists may cause irritation
SENSITIZATION	Unlikely to be a skin sensitizer
REPEATED DOSE TOXICITY	Unlikely to be a hazard

EXPOSURE CONTROLS/PERSONAL PROTECTION

EXPOSURE CONTROLS	The level of protection and types of controls necessary will vary depending upon potential exposure conditions. Select controls based on a risk assessment of local circumstances.
PERSONAL PROTECTIVE EQUIPMENT	Personal protective equipment (PPE) should meet recommended national standards.
RESPIRATORY PROTECTION	Respiratory protection is not required under normal conditions of use in a well-ventilated workplace. In accordance with good industrial hygiene practices, precautions should be taken to avoid breathing of material.
EYEPROTECTION	Eye protection is not required under normal conditions of use. If material is handled such that it could be splashed into eyes, wear splash-proof safety goggles or full-face shield.
PROTECTIVE CLOTHING	Skin protection is not required under normal conditions of use or for single, short-duration exposures. For prolonged or repeated exposures, use impervious chemical-resistant boots, gloves and/or aprons over parts of the body subject to exposure.

Appendix A

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

ECOLOGICAL INFORMATION

CHEMICAL CONTENTS	CHEMICAL COMPOUNDS	SIGNIFICANCE	ACCEPTABLE LEVELS
CHLORIDE	Cl	Presence is salty, corrodes pipes pumps and plumbing fixtures Not harmful to health	Maximum safe level in drinking water: 250 mg/L 1
PHOSPHORUS	PO4	Presence leads to growth of aquatic algae and plants	Maximum safe level in rivers: 0.1 mg/L 2
AMMONIA NITRITE NITRATE	NH4 NO2 NO3	Presence of Ammonia in high levels causes toxic buildup in tissues and blood. Presence of Nitrite and Nitrate in high levels increase heart rate, nausea and headaches.	Ammonia Range for safe level in water: 0.25 mg/L to 32.5 mg/L 3 Maximum safe levels of Nitrite and Nitrate: 1 mg/L and 10 mg/L respectively 3

CHEMICAL	CONTROL (mg/L)	10:1 (mg/L)	20:1 (mg/L)	ACCEPTABLE LEVELS
Cl	0.197	30.183	44.9	Maximum safe level in drinking water: 250 mg/L1
PO4	0.002	0.072	0.026	Maximum safe level in rivers: 0.1 mg/L2
NH4	ND	1.19	ND	Ammonia Range for safe level in water: 0.25 mg/L to 32.5 mg/L3 Maximum safe levels of Nitrete and Nitrate: 1 mg/L and 10mg/L respectively 3
NO2	0.0005	0.0058	0.0024	
NO2+NO3	0.004	0.057	0.011	
DIC6	.087	36.18	37.53	In most surface water 3.5 to 350 ppm4
DOC	0.8272	56.96	50.99	Surface waters typically show thousands of mg/L depending on the source 5

Appendix A

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

ECOLOGICAL INFORMATION

CONCENTRATIONS OF IMPORTANCE (PPM)	CONTROLS	10 TO 1	20 TO 1	IGNIFICANCE
Ca (Calcium)	0.51	60.25	43.31	In water, high levels can contribute to water hardness and may affect industrial processes and water distribution systems. In soil, excessively high levels can interfere with the uptake of other essential nutrients by plants. Permissible levels of Calcium is 75ppm according to WHO for drinking water 7
K (Potassium)	1.09	4.43	7.33	Potassium is not a concern as a pollutant. Permissible levels of Potassium is 12ppm according to WHO fos drinking water 7
Mg (Magnesium)	0.31	6.78	5.99	Major contributor to water hardness, along with calcium. High levels in irrigation water can contribute to soil salinity and affect plant growth. It may be necessary to consider the contect in irrigation water to prevent soil degradation. Permissible levels is 50ppm according to WHO for drinking water 7.
Na (Sodium)	2.15	5.89	58.4	High sodium levels contribute to high salinity. Permissible levels is 250ppm according to WHO for drinking water 7.

DISPOSAL CONSIDERATIONS

MATERIAL DISPOSAL	Recover or recycle if possible. It is the responsibility of the waste generator to determine the toxicity and physical properties of the material generated to determine the proper waste classification and disposal methods in compliance with applicable regulations. Do NOT dispose into the environment, in drains or in water courses.
CONTAINER DISPOSAL	Dispose in accordance with prevailing regulations, preferably to a recognized collector or contractor. The competence of the collector or contractor should be established beforehand.
LOCAL LEGISLATION	Dispose in accordance with applicable regional, national and local laws and regulations.

Disclaimer

No warranty of merchantability, fitness for any particular purpose, or any other warranty is expressed or is to be implied regarding the accuracy or completeness of the information provided above, the results to be obtained from the use of this information or the material, the safety of this material, or the hazards related to its use. No responsibility is assumed for any damage or injury resulting from abnormal use or from any failure to adhere to recommended practices. The information provided above, and the material, are furnished on the condition that the person receiving them shall make their own determination as to the suitability of the material for their particular purpose and on the condition that they assume the risk of their use. In addition, no authorization is given nor implied to practice any patented invention without a license.

Appendix B

Final Report

Solid Earth Technical Data Sheet (TDS)

Appendix B

SOLID EARTH TECHNICAL DATA SHEET (TDS)

This technical data sheet (TDS) of Solid Earth (soil solidifier, stabilizer and dust control product) is a comprehensive document that provides all relevant data about the product to potential customers, engineers, contractors, and other stakeholders. It is designed to give a clear understanding of the product's composition, features, benefits, application methods, safety information, and technical specifications.

Product Name and Description:

Solid Earth is a unique innovative liquid polymer soil solidifier/stabilizer installed using existing or imported soil to produce solid, water-resistant, load-bearing roadways, pathways and other solid, high compressive strength surfaces without adding pollutants to the substrate or ground water. Used to stabilize ground, slope or embankment soil, Solid Earth effectively reduces mud, dust and erosion. Solid Earth's 15 years of successful testing in the field is now supported by a comprehensive study conducted by a team of scientists from the Arizona State University School of Sustainable Engineering and the Built Environment headed by FORTA Professor of Pavement Engineering Kamil Kaloush, Ph.D., P.E.

ASPECT/ITEM	VALUE/DESCRIPTION
APPEARANCE	White liquid
ODOR	Resinous-almond
PH VALUE	4.58
BOILING POINT/RANGE	98.2 °C
FREEZING POINT/RANGE	-1.25 °C
VISCOSY, LV-3 @ 20RPM	443.9 cps @ 7.4 Torque %
SPECIFIC GRAVITY OR DENSITY	8.62 lb./US gal - 1.032g/ml
SOLUBILITY	Soluble in water and other solvents

Composition/Information on Ingredients:

- Ingredients: Binder (~85%)
- Blend of mineral oils and non-ionic surfactants (~0.3%)
- Water (~14%)

Appendix B

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

Performance Data:

ASPECT/ITEM	Value/Description
EFFICACY DURATION	Durability Resistance: Wetting and Drying (ASTM D559). Weight loss of soils treated with Solid Earth is about 4.9%. The Portland Cement Association establishes a Maximum limit of 14%. Solid Earth duration is about 3 times lower of the maximum limit established for Portland Concrete. Consistent volume change indicates good dimensional stability.
STRENGTH OR STABILITY ENHANCEMENT METRICS	Unconfined Compression Strength Testing (UCS) /(ASTM D2166) shows that soils treated with Solid Earth can reach 319.2PSI. A soil stabilized with Lime 6% can reach 92PSI. Solid Earth can improve the UCS up to 3.5 times more than conventional methodologies.
WIND EROSION CONTROL AND DUST CONTROL EFFECTIVENESS	Wind Erosion Resistance using PI-SWERL (Portable In-Situ Wind Erosion Laboratory). When soils treated with SE are exposed to wind forces simulated in a controlled environment at 12 m/s and 16 m/s, the erosion is reduced in 90% and 84% respectively.
OPTIMAL CONDITIONS FOR USE	Solid Earth should be blended with water in a ratio of 20:1 (Water:Solid Earth). Optimal performance can be found in granular soils such us crusher fines, sand, etc. According to the Proctor Modified Test (ASTM D1557), the optimal Solid Earth solution (20:1) is 12% to obtain a maximum density of 19.7kN/m3.

Appendix B

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

Application Instructions:

Aspect/Item	Value/Description
Preparation of the surface/soil prior to application (varies with type of application)	Scarify, till or loosen dirt or gravel surface to a depth of 3 to 4 inches if needed. Apply 2 coats of material with pressurized spray equipment until saturation occurs. Allow brief curing, then compact with roller if necessary. Apply the final finish coat and cure until hardens before introducing traffic.
Recommended application rates and methods (varies with type of application)	Solid Earth should be blended with water in a ratio of 10:1 to 20:1 (Water:Solid Earth). Optimal performance can be found in granular soils such us crusher fines, sand, etc.
Curing time and conditions	Curing should be done at environmental conditions. The slower the time of curing the better performance results.
Equipment needed for application (varies with type of application)	Red Fire Hose Nozzle, Skid Steer Loader, Grader (i.e. Gannon), 2-ton Water Truck or Water Buffalo, 2-ton Double Steel Drum Roller

Appendix B

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

Safety Information:

Aspect/Item	Value/Description
Hazard identification	Health Hazards: Categories 1-4 and 2A 
Precautionary statements for handling and storage	Good organization is needed for storage, relocate, usage, and application of this material to avoid leaks and spills.
Personal protective equipment (PPE) recommendations	Insufficient ventilation: wear respiratory protection. Gloves. Protective clothing. Safety glasses or chemical goggles as appropriate to prevent eye contact.
First aid measures	First-aid measures section on the safety data sheet (MSDS) of the product.
Fire-fighting measures	Not considered flammable, however, for eventual incidents use extinguishing media appropriate for surrounding fire. Do not use a heavy water stream. Use of heavy stream of water may spread fire.
Accidental release measures	In the occasion of a spill or leak of material, barrier and absorb material with inert material and scoop up material. As with all spills, diminish material incoming water systems.

Appendix B

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

Environmental Impact:

Aspect/Item	Value/Description
Biodegradability and environmental persistence	Major constituents are expected to be willingly biodegradable
Eco-toxicity	Plant and water quality impact expected to be very low.
Precautions for environmental protection	Minimize product runoff during application. Material will dry to a solid binder that is highly resistive to wash out.
Disposal considerations	Dispose of material in following all pertinent federal, state/provincial and local laws and policies. Waste classification and observance with related laws are responsibility exclusively of the waste originator.

Technical Support and Services:

- Hadar Rahav
  President
- hadar@solidearthinc.com
- Office: 480-446-9000
- Cell: 602-625-0954

Packaging:

- 5 Gallon Buckets = 45 lbs.
- 250-gallon Totes = 2350 lbs.
- Tote Dimension = 48”x 40”x 45” (tote sizes vary)

Appendix B

SOLID EARTH MATERIAL SAFETY DATA SHEET (MSDS)

Storage and Handling:

Store product in an unopened container in a dry location. Storage information may be indicated on the product container labeling.

Optimal Storage: 8 °C to 21 °C. Storage below 8 °C or greater than 28 °C can adversely affect product properties. Material removed from containers may be contaminated during use. Do not return product to the original container. Solid Earth Inc. cannot assume responsibility for product which has been contaminated or stored under conditions other than those previously indicated. If additional information is required, please contact your local Solid Earth representative.

Conversions
(°C x 1.8) + 32 = °F

Inspect containers and storage area regularly for signs of leakage or damage. Store in the original, labeled container.
Store in a well-ventilated place. Keep container tightly closed. Keep in a cool and dry area away from direct sunlight.

Transport Information:

UN number	Not applicable
UN proper shipping name	Not applicable
Transport hazard class	Not applicable
Packaging group	Not applicable
Environmental hazards	No
Transport in bluk, if applicable	Not applicable
Special Precautions/provisions	NIL

Storage and Handling:

· Hadar Rahav
President
· hadar@solidearthinc.com
· office: 480-446-9000
· cell: 602-625-0954

· SOLID EARTH INC.

· 1027 E. Curry Rd.
Tempe, Arizona 85288, USA

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