Characterizations of Soil Layers Artificially Deposited on Glass and Photovoltaic Coupons

by

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ABSTRACT

The deposition of airborne dust, especially in desert conditions, is very problematic as it leads to significant loss of power of photovoltaic (PV) modules on a daily basis during the dry period. As such, PV testing laboratories around the world have been trying to set up soil deposition stations to artificially deposit soil layers and to simulate outdoor soiling conditions in an accelerated manner. This thesis is a part of a twin thesis. The first thesis, authored by Shanmukha Mantha, is associated with the designing of an artificial soiling station. The second thesis (this thesis), authored by Darshan Choudhary, is associated with the characterization of the deposited soil layers. The soil layers deposited on glass coupons and one-cell laminates are characterized and presented in this thesis. This thesis focuses on the characterizations of the soil layers obtained in several soiling cycles using various techniques including current-voltage (I-V), quantum efficiency (QE), compositional analysis and optical profilometry. The I-V characterization was carried out to determine the impact of soil layer on current and other performance parameters of PV devices. The QE characterization was carried out to determine the impact of wavelength dependent influence of soil type and thickness on the QE curves. The soil type was determined using the compositional analysis. The compositional data of the soil is critical to determine the adhesion properties of the soil layers on the surface of PV modules. The optical profilometry was obtained to determine the particle size and distribution. The soil layers deposited using two different deposition techniques were characterized. The two deposition techniques are designated as "dew" technique and "humidity" technique. For the same deposition time, the humidity method was determined to deposit the soil layer at lower rates as compared to the dew method.

Two types of deposited soil layers were characterized. The first type layer was deposited using a reference soil called Arizona (AZ) dust. The second type layer was deposited using the soil which was collected from the surface of the modules installed outdoor in Arizona. The density of the layers deposited using the surface collected soil was determined to be lower than AZ dust based layers for the same number of deposition cycles.

To,
My mother and father for their unyielding belief, my brother and sister-in-law for their love and constant support.

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TABLE OF CONTENTS

CHAPTER Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

Figure Page

1.0 INTRODUCTION

1.1 Background

The global solar energy market already accounts for more than 1% of the total energy market. This is significant because of the time frame in which it has achieved this feat. It is thus only to be expected that the global energy market share for solar will only rise. This is because of the abundance of solar radiation, especially in the countries near the equator or the sun-belt countries [1] such as the Middle East, Parts of America, Africa, etc. as seen below in the Figure 1.

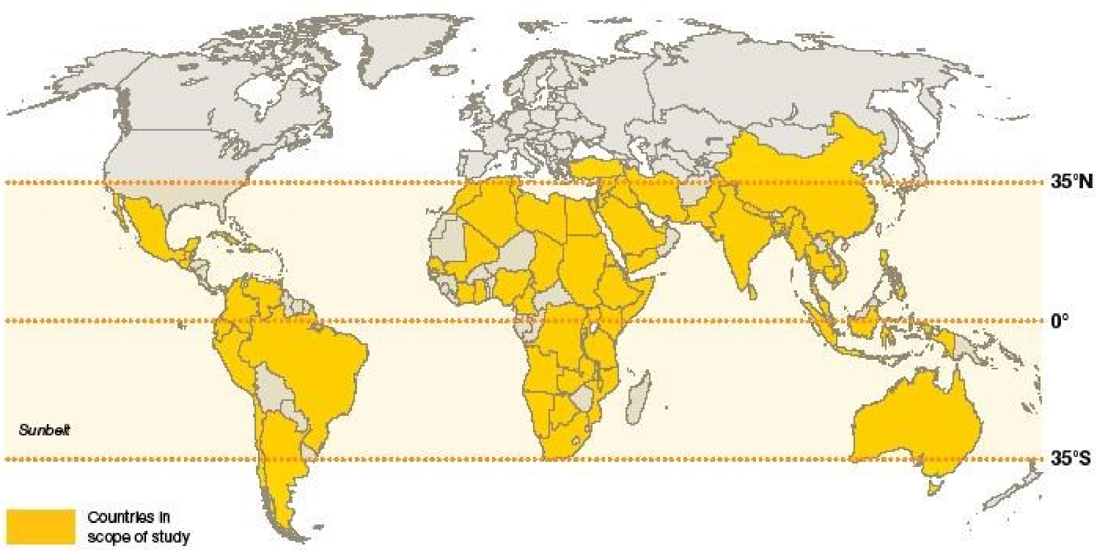


Figure 1: World Map Showing the Sun-Belt Countries *[1]*

There have been news of a large number of developed and developing countries setting goals of reaching 20-30% of their energy demands by 2050 using clean energy. Solar photovoltaic (PV) is one the primary technologies being used to meet these goals and thus has seen tremendous growth in the amount of installation seen around the globe as an effort to attain the targeted energy production levels. The PV industry works on the simple principle of absorbing photons and releasing electrons into a circuit. However if the amount of photons incident on the modules changes or reduces, the amount of electrons released into the circuit can be affected. This can happen under various conditions, such as if there are clouds overhead blocking the sun's rays, or if there is some shading on the modules due to some object, or if there is a deposition of dust on the module surface [2].

1.2 Why is Soiling Important?

The dust deposition on the module can be as a result of water vapor mixing with fine soil particles, soot, or aerosols in the atmosphere. Especially during dust-storms and in the aftermath of a windy day, a lot of soil can be accumulated on the modules.

Different climatic conditions can have different effects on the modules performance. A region like Arizona will experience a lot of loss due to soiling during the dry season [3] with up to 0.06% losses of power per day of the dry season. However the same might not be true for a region like Germany where it experiences a lot of rainfall, thus having little to no soiling effect. Looking into the weather conditions coupled with the soil type, it has been seen that the effects on the photovoltaic modules can range from various forms of degradation to simple loss of power. For example, shading of the module along with the presence of moisture which can permeate through the back-sheet of the PV module, can lead to delamination of the module. Again, simple shading of parts of the module can lead to possible hot spots creation which is true for dry, desert climate with little moisture content in the atmosphere, thus causing less moisture to permeate through the back-sheet and the edge seals of the module.

Figure 2: A Dust Storm in Mesa AZ (Image Source: ABC news July 27, 2014)

As a result, there is an effect on the performance of the modules. This, in turn can ultimately result in losses in revenue or decrease in energy production. As already seen, along with the loss in energy production, the modules can also experience severe degradation due to the continuous shading of parts of the module, leading to possible hot spots creation and performance losses. The loss in energy production is obviously not good for the industry, where the energy market is as competitive as seen today. To understand the effects of soiling on the modules, a number of studies have been previously done by research institutions to determine better methods or technologies to keep the modules cleaner and production higher. John et al [4], made a comprehensive study on the types of methods which can be used for studying the effects of soiling on PV modules, for different geographic locations (having different climatic conditions). The amount of soiling seen on a module at a particular location, can be either mild soiling, moderate soiling or heavy soiling, each of which will have different effects on the performance and degradation of the module.

1.3 Scope of Work

This thesis is a part of a twin theses. This thesis looks into the soil characterization tests done on different samples (Mini Module, Coupon and Glass Slide samples) used by artificially soiling the samples in the Artificial Soiling Chamber developed at Arizona State University- Photovoltaic Reliability Laboratory (ASU-PRL). This development of an artificial method of soiling proved to be a big learning experience in understanding the various nuances associated with uniform soil deposition on a module.

Researchers have been working towards building a standard testing equipment to replicate the outdoor soiling conditions and test out the soiling effects on the modules [5]. However, different research laboratories have veered towards different techniques and processes to achieve the same cause, that is, of analyzing the effects of soiling on a module. As non-uniform soiling on samples will lead to obvious different results every time, the need to test out the soiling effects under uniform soiling is of paramount importance. However, as has already been seen, the number of ways of achieving this is numerous. This has led to a number of different approaches for the soil deposition techniques, such as using a solution of soil plus water or soil plus acetonitrile for the adhesion of the soil on the module, along with keeping the module samples at an angle or horizontally, as required. Different methods of artificial soiling come with different costs and this will lead to variation of results if the exact method of artificial soiling can't be replicated everywhere. The next step would obviously be to look at methods of cleaning the module at the least cost with highest efficiency. However, now in the purview of this thesis, the cleaning methods are out of scope.

It has come to the fore that soiling of a module, especially in an indoor setup [6], could lead to different results if the procedures followed vary from one testing method to another. The need for a standard testing equipment or process and a number of set characterization tests could potentially help the industry determine the long term effects of soiling on the various components of a module and thus try and create modules with higher reliability. This thesis works on the results of a design made at ASU-PRL and aims to determine the performance effects on a module by soil characterization tests on the module after a set number of accelerated soiling cycles. The presence of different components in the airborne soil can lead to different effects on the performance. Thus, this thesis aims to verify the uniformity of the soil deposition and identify the cause and effects of the soil deposition on the samples.

2.0 LITERATURE REVIEW

2.1 Background

Solar PV panels basically work on the technology of semiconductors generating electrons on absorption of photons. Looking at the basics, a crystalline PV module is made of a number of layers joined together. The top layer of a crystalline PV module is basically made of glass followed by typically EVA and the top layer of the Silicon wafer. Generally the top layer of the wafer is the negatively doped Silicon or the n-type. Below the n-type layer is the p-n junction layer where the carriers get collected on either side of the junction to create a drift current layer. Below the junction is the p-type layer which is the positively doped layer consisting of holes as carriers. Below the p-type layer is the encapsulant and the back sheet. This is then enclosed in an aluminum frame and a glass cover which protects the module from the top. The glass cover is necessary as it allows most of the irradiance to pass through while protecting the module from any external damage. The glass used nowadays is usually tempered glass instead of annealed glass for the sake of the protection of the people installing or removing the modules and also because it is a cheaper option in the long run.

Solar power generation is the culmination of a number of components working together. This includes the modules, the inverters, the tracking system, the wires, the mounting racks, etc. The components apart from the modules are called the balance of system. All the components in the PV system respond differently to the weather conditions. For example, the electronic components such as the inverter and the circuitry needs to be protected and hence the need for an enclosure for the inverter is of paramount importance.

The photovoltaic module designs have gradually evolved to capture the maximum amount of irradiation and produce the maximum power output within the safety standards set by the industry. However due to the weather conditions, the deposition of soil, along with other particles in the atmosphere on the modules can have a detrimental effect on the performance of the modules. This detrimental effect on the modules can lead to losses in terms of the revenue it would have generated. It can also lead to losses in terms of the failure of some component in the PV system. Hence, the replication of the soiling conditions and to study the effects of the soiling on the performance of the modules has been the focus of many research laboratories over the last decade. However having a standard testing method and setup to simulate the soiling conditions has been a glaring need in the industry. This thesis is aimed at looking at the soil characterization of the layers deposited artificially on a module using the artificial soiling station developed at ASU-PRL to understand if it can be considered as a potential design for the standard test setup.

2.2 Literature Review

Soiling had been identified as a major problem for the photovoltaic industry from its very onset. From the study made by Salim et al [7], we have seen the adverse effects of soiling as there is evidence of a 32% reduction in the performance of a solar array due to dust accumulation on the array. In the age of competitive energy pricing, there have been reports where an average loss of around 1-6% can be seen annually, which could also go up to 27% based on the site specific conditions. Based on the works of Sravanthi et al [8] at ASU-PRL, angle of incidence studies showed the change in critical angle for the air/glass interface to shift from 57º to 40º for the air/soil/glass interface.

Burton et al [9] showed a similar development of an indoor soiling station with a spray gun using traceable NIST soil by which a distinctive relationship between deposition and performance of the module could be determined. The procedure followed for his method is discussed as follows: Arizona Road dust (ISO 12103-1, A2 fine test dust nominal 0-80 micron size, Powder Technology Inc., Burnsville, MN, USA) was mixed with a soot mixture composed of 83.3% diesel particulate matter, (NIST Catalog No. 2975); 4.2% unused 10W30 motor oil, 4.2% α-pinene, (Catalog No. AC13127-2500, Acros, Organics, Geel, Belgium) in a glass jar and tumbled without milling media in a rubber ball mill drum at 150 r/min for 48 to 72 h. The composition was varied to include 3 wt%, 10 wt% and 25 wt% soot mixture and samples were prepared on a 100g total solid basis. The composition of the varying soot mixture did not represent any specific location, but on an average, represented the soot content present in a few locations. For application onto the samples, the grime mixture was combined with Acetonitrile, ACN (HPLC grade, Sigma Aldrich, St. Louis, MO, USA) in a ratio of 3.3 g to 275 ml and was sprayed using a HVLP (high velocity low pressure) gun held approximately 30 cm from the coupon surface. The samples were sprayed from right to left for a duration of 1-3 seconds, and to obtain high soiling density, multiple coatings were sprayed. The glass coupons before and after soiling were weighed with a Mettler Toledo (Columbus, OH, USA) XP205 balance with 0.00001 g resolution and characterization tests were also performed. Variations in the grime mixture was produced by incorporating major optical components, like iron oxide and in-house synthesized gothite, as primary spectral components. After soil formulation and application, characterization tests like current-voltage and QE measurements were carried out on soiled glass samples.

Also, the work of Vidya et al [10] for the indoor soiling station and the reflectance and QE studies made on the sample showed a trend with soil density. The indoor soiling method developed at ASU-PRL was instrumental in understanding and developing a newer, modified version to replicate the natural conditions of soiling on the modules. One of the distinctive aspects of the soiling methods developed was the use of Acetonitrile in the case of Vidya et al [11] to hold the soil on the surface of the sample module which has now been replaced with water. Taking inspiration from a method developed at Sandia National Laboratories, the setup at ASU PRL had the following procedure- AZ road dust was formulated artificially by mixing the standardized soil or particulate matter (AZ fine test dust) with HPLC (High Performance Liquid Chromatography) grade acetonitrile. The soil solution was then sprayed uniformly on the test module using a HVLP (High velocity low pressure) spray gun with a 1 mm nozzle from Centralpneumatic. The spray gun had an air pressure range of 30-40 PSI, air consumption of 12 CMF @40PSI and cup capacity of 20 fl.oz. The spray gun was used to soil a sample and the factors affecting the soil deposition include the following: Fan direction, pattern adjustment and fluid adjustment.

The soiling variation was corrected by having the fan direction of the spray gun along the horizontal direction. The pattern knob was adjusted at round/ closed pattern to get more uniform soiling. The artificial soiling chamber constructed to test the procedure was constructed in a cuboidal structure and an air bag from Sigma Aldrich Corporation was used. The distance maintained between the test sample and the spray gun was around 2.5

feet. Maintaining the chamber vertically the uniformity was higher by using the pulse-spray approach. The soil density was measured using the measurements on the commercially available microscopic slides to check the amount of soil deposited before and after soiling.

The soil characterization process also involved using a spectroradiometer to measure the reflectance. Next up is the Quantum efficiency measurements which was taken using the QEX12M quantum efficiency measurement system. The measurements using the QE machines requires proper calibration before use. The measurements were taken before and after soiling. Among the soil characterization tests done, the current-voltage measurements before and after soiling, along with the reflectance and the QE tests were done to measure the effects of the soiling on the sample.

John et al [4] showed the angle of incidence studies for the soiled modules showed a relative difference for the various type of locations and the soil types. The work by Weber et al [12] on the cleaning methods used by the industry shows the effects of the angle of impact of the soil particles on the glass of the modules. A degradation trend in the transmittance properties for the samples were also studied. The soil densities obtained for this method was around 1.5 g/m^2 per cycle. The I_{sc} losses for the same were seen to be in the range of 1.4-8.2% for an increasing soil density of 0.18-1.8 g/m^2 for the mono-si coupon and in the range of 0.6-1.55 g/m^2 for the poly-si mini module.

Jim John [4], in his doctoral thesis, looks at two strategies to evaluate the soiling effects on PV modules at a geographical location. It also discusses the methods and techniques used to look at the spectral and angular losses on the PV modules. It was found that the moderately soiled modules showed short circuit current (I_{sc}) losses of about 10% and the heavily soiled modules showed short circuit current (I_{sc}) losses of around 41%. Besides this, the losses in the spectral reflectance and quantum efficiency losses were also evaluated. The results showed the increase in reflectance of around 58.4% for moderately soiled PV modules and 87.2% for heavily soiled PV modules. Another interesting result found was the effect of various soil types on the soil characterization tests. The results showed that the dust collected from the module surface at Mumbai, India showed higher spectral loss than other places such as Jaipur, India. The results also found that the worst affected technology by soiling is the Amorphous silicon (17.7%) followed by Cadmium Telluride (15.7%), Crystalline Silicon (15.4%) and CIGS (14.5%). One significant factor to be understood is that dust-storms are not the singular cause of soiling in different climatic conditions, especially the desert, dry conditions. Also, there have been reports of high levels of losses due to soiling in most of the sun-belt countries which has led to a huge number of studies in soiling loss. Ideally the irradiance losses seen on a module is due to the angle of incidence being different from the normal. As such, there is always some amount of loss involved due to the top reflection of the glass cover and the highly reflective nature of the crystalline Silicon surface. The changes in the angle of incidence can lead to loss of current generation in the modules thus resulting in revenue losses. The ideal scenario of the PV industry would be to have normal incident radiation on a clean module at all times, with little to minimal reflection losses due to the surface reflection. The deposition of a layer over the standard layers of the module can cause changes as shown below. Hence it was suggested that while calculating the losses, it is better to collect the soil deposited on the module surfaces and carry out the experiments using that soil as the basis for that particular location, as the soil will be affected by the climatic conditions of that location.

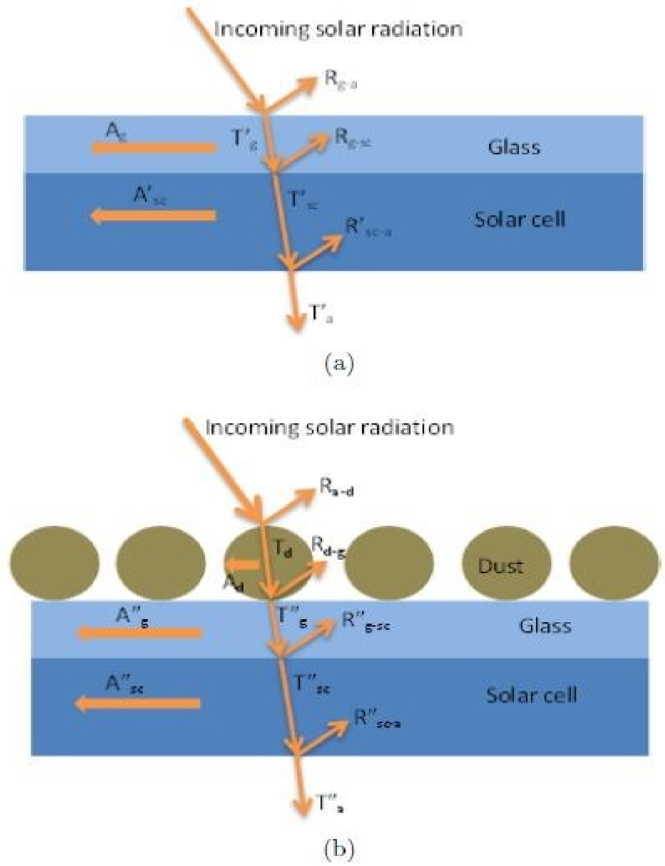


Figure 3: (a) Angle of Incidence of Light on a Clean Module & (b) Angle of Incidence Distorted Due to soiling *[4]*

Artificial soiling station setups have been created by a number of different research laboratories. The setup made at PI Berlin uses a technique with compressed air and soil sprayed onto the sample module kept at various tilt angles. The characterizations revealed the power losses were affected by the spray angle of the soil spray. The study also focused on the effects of the type of glass cover for the module coupons on the module performance. The results found that some glass sample exhibited better self-cleaning properties as opposed to traditionally used tempered glass. Studies further go into the cleaning methods and their effects on the performance and degradation of the module samples. But the cleaning methods are outside the purview of this thesis.

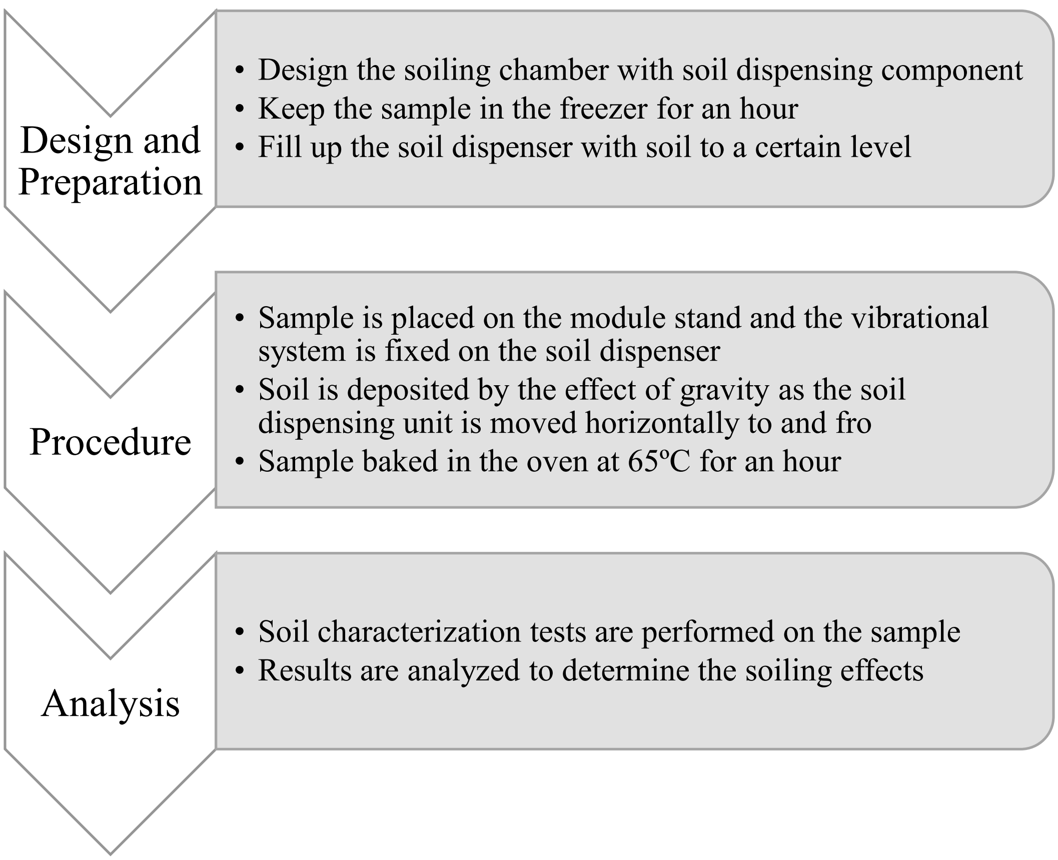
3.0 METHODOLOGY

3.1 Soil Deposition Technique

3.1.1 Gravity Method/Dry Method

The idea behind this method was to simulate the conditions seen in a dry, desert environment like Arizona. As the process developed, the realization that this particular process had some serious flaws became obvious. This model was, in theory to work simply on the effects of gravity and not by any other means.

This method can be briefly summarized in the following steps:



A model was conceptualized, designed and fabricated at ASU-PRL using SolidWorks for the modelling and 3d printing for the fabrication. This model used a soil deposition scheme with a soil dispensing component along with using a vibrational system for uniform deposition on the modules. The critical component of this method was the soil dispensing station, which had a funnel shaped soil collecting section, connected with a slit to allow a regulated amount of soil to pass through it. A mesh of varied sizes was used to hold the regulated soil in place.

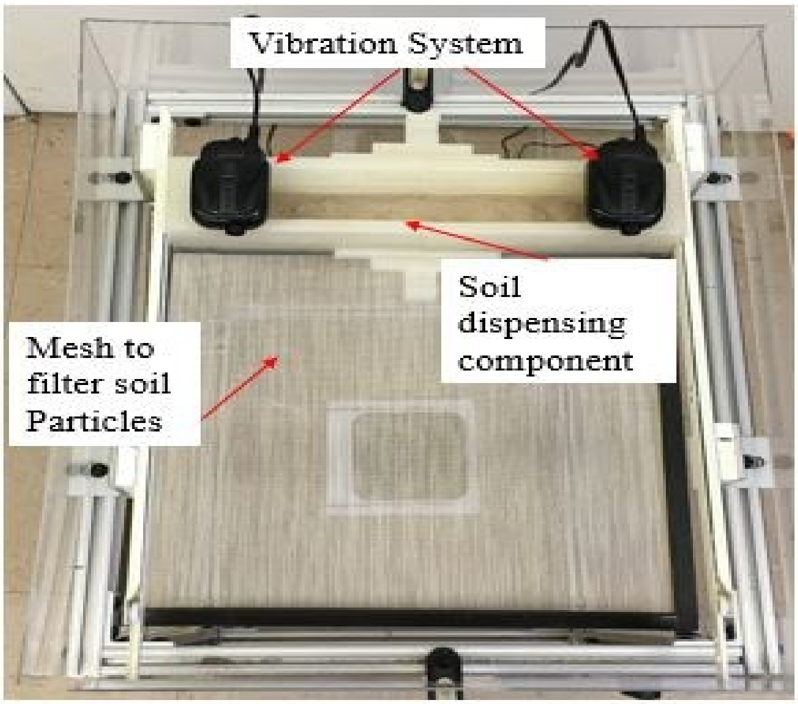


Figure 4: Top View of the Dry Method Setup

The theory is that the soil deposited on the coupon needs to stick for subsequent layers to stick onto the previously deposited layers. Hence a layer of moisture needs to be present on the coupon surface before being baked. Baking the coupon means heating the module coupon in an oven at 65º C for an hour. This is necessary as the layer of the soil deposited on the coupon gets firmly attached onto the glass or the previous layer of soil.

The coupon is first placed in the freezer for an hour which creates a layer of moisture on the glass surface once the coupon is taken out. Then, the coupon is placed at a particular fixed orientation on the base of the chamber. A vibrational system is then used to create vibrations on the soil dispensing component which allows a small amount of soil to be released from the component. A to and fro motion is then provided on the component horizontally which allows a steady, thin stream of soil to fall onto the coupon.

This motion is provided manually by timing the oscillations using a stopwatch. However the usage of the soil dispersing component is not enough for soil deposition. A mesh is used which acts as the main component holding the soil in check while the vibrational systems used creates vibrations to allow the soil to fall through the mesh onto the module.

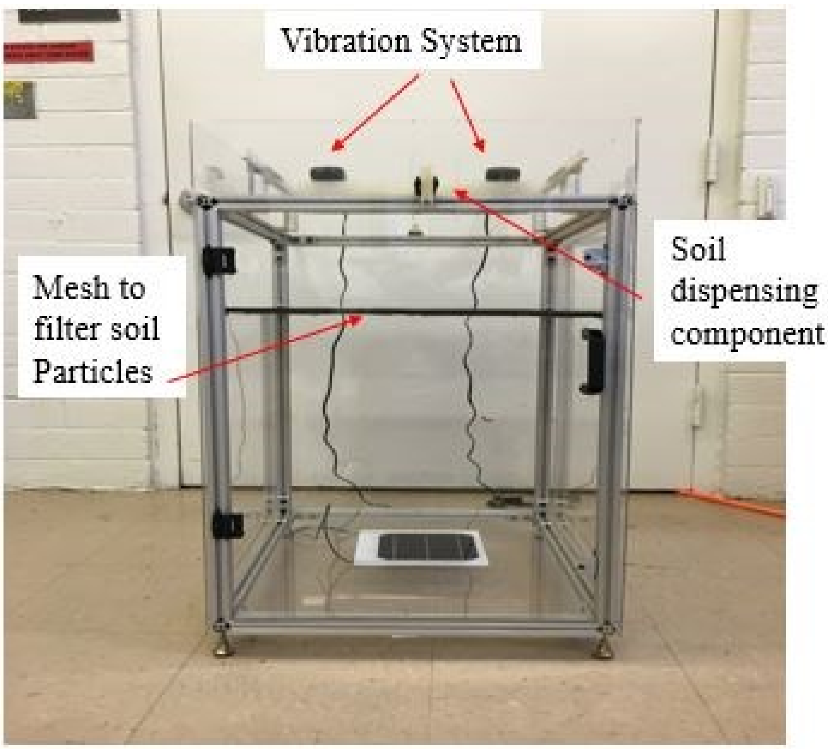


Figure 5: Setup for the Dry Method Showing the Front View with the Soil Dispensing Component and the Vibrational System

However, it became evident that the deposition of the soil onto the module also depends on the mesh size which would prove to be a major factor. The soil particle size was highly dependent on the mesh gap and hence evidence of clumps could be observed. This were some of the issues faced during the method refinement and development process.

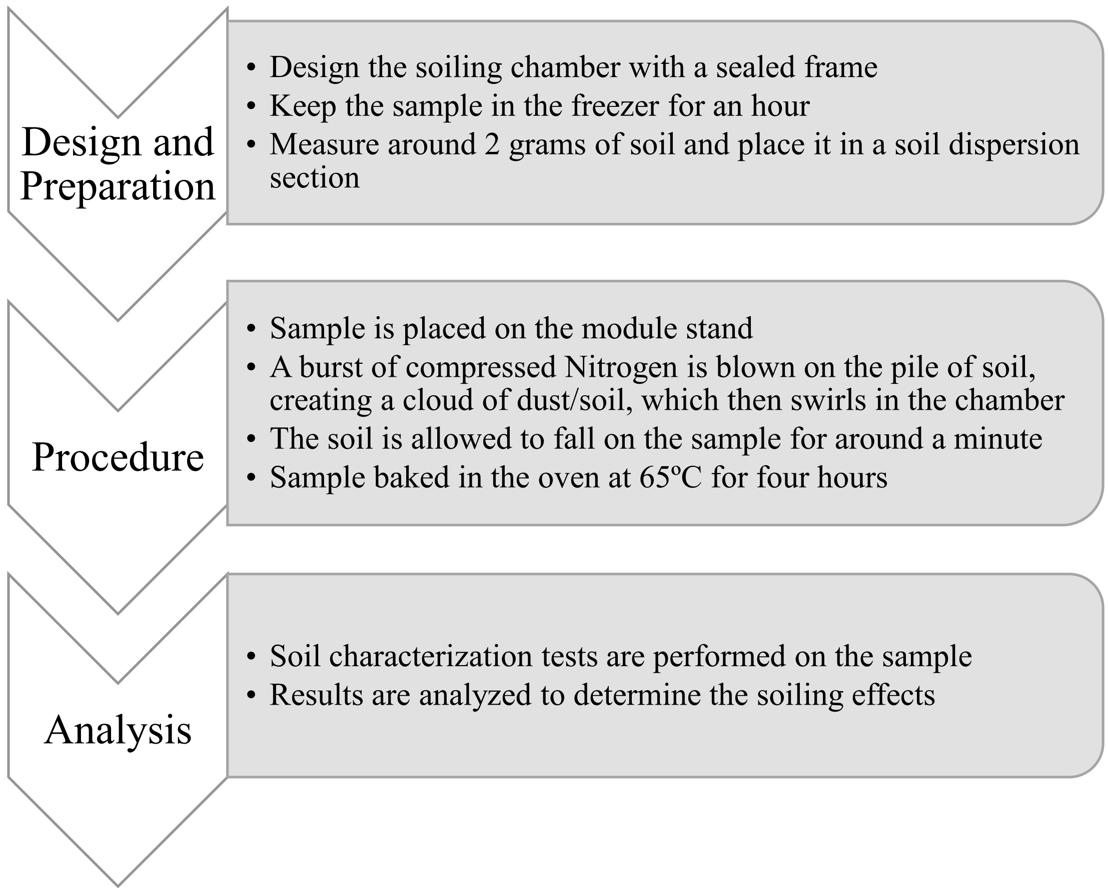
Then, the coupon is subjected to a number of soil characterization tests such as:

- Reflectance on the mono crystalline cell
- QE on the module(before and after deposition)
- Isc measurement of each individual cell
- IV for the module
- Particle Size Frequency and Soil composition
- Particle size distribution using optical microscope

This is used to identify the effects of soiling on the coupons. These soil characterization tests were selected to give an overall idea of the effects of soiling and the specific region of the spectrum which would be affected most by the soil layer.

3.1.2 Dew Method

This method was created to replicate the dew cycle experienced by the modules in almost every climate. As the module experiences a high irradiation amount during the day and experiences an extreme change in weather conditions at night, the module goes through a number of thermal cycles which leads to the formation of frost on the module during night and the deposition of soil throughout the day which helps stick the deposited soil by being baked under the sun. This method can be summarized into the following steps:



In the same soiling chamber designed at ASU-PRL, the soil deposition component is dismantled and kept aside. Instead, a small insert is made on the bottom side wall to allow the insertion of a nozzle for the compressed gas. The concept for this method is the creation of a dust cloud by the sudden release of compressed gas onto a small measured quantity of soil in a small chamber. This sudden burst of compressed gas would create a vortex of swirling gas which would carry the small soil particles with it and deposit the same onto the sample by the effects of gravity. The coupon sample used in this method is first kept in the freezer for an hour.

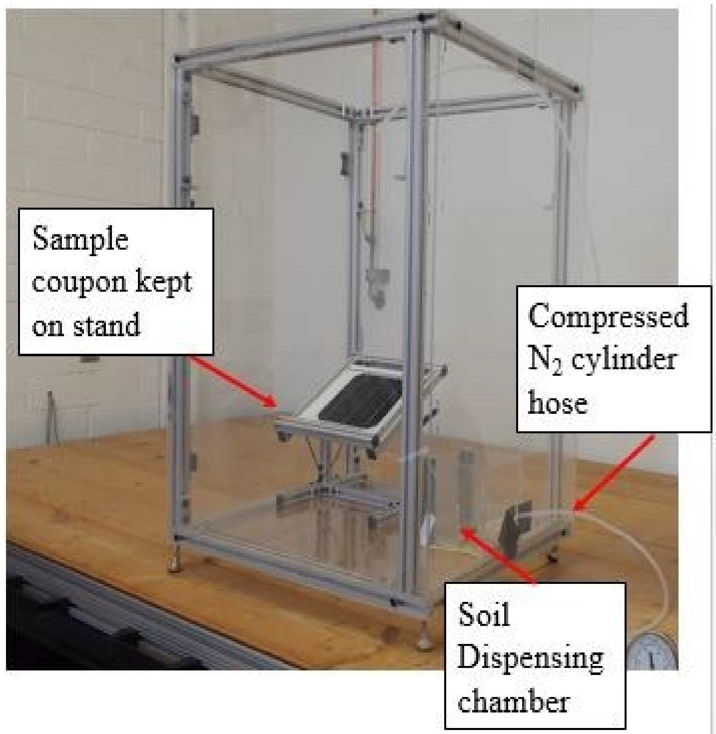


Figure 6: Dew Setup with Stand and Coupon Showing the Compressed N2 Gas Connections

As the module sample placed inside the soling station would be taken out from the freezer, a film of water would be created on the sample surface due to condensation. This film of water would prevent the soil particles getting deposited on the sample from sliding off. After placing the coupon on the stand, the compressed N_2 gas cylinder is used to give a quick burst of 1-2 seconds of N_2 gas. This would result in the creation of a soil cloud which would swirl around in a turbulent manner. Now after creating the cloud of soil, the swirling cloud stabilizes slowly it deposits onto the module. This deposition is allowed for around one minute. After one minute, the sample is taken out and placed in an oven to bake the soil. This baking is done at 65 ºC for four hours. This baking step is important as it cements the soil deposited onto the sample and prevents the layer from falling off. After four hours, the samples are taken out and the characterization tests are done on the sample.

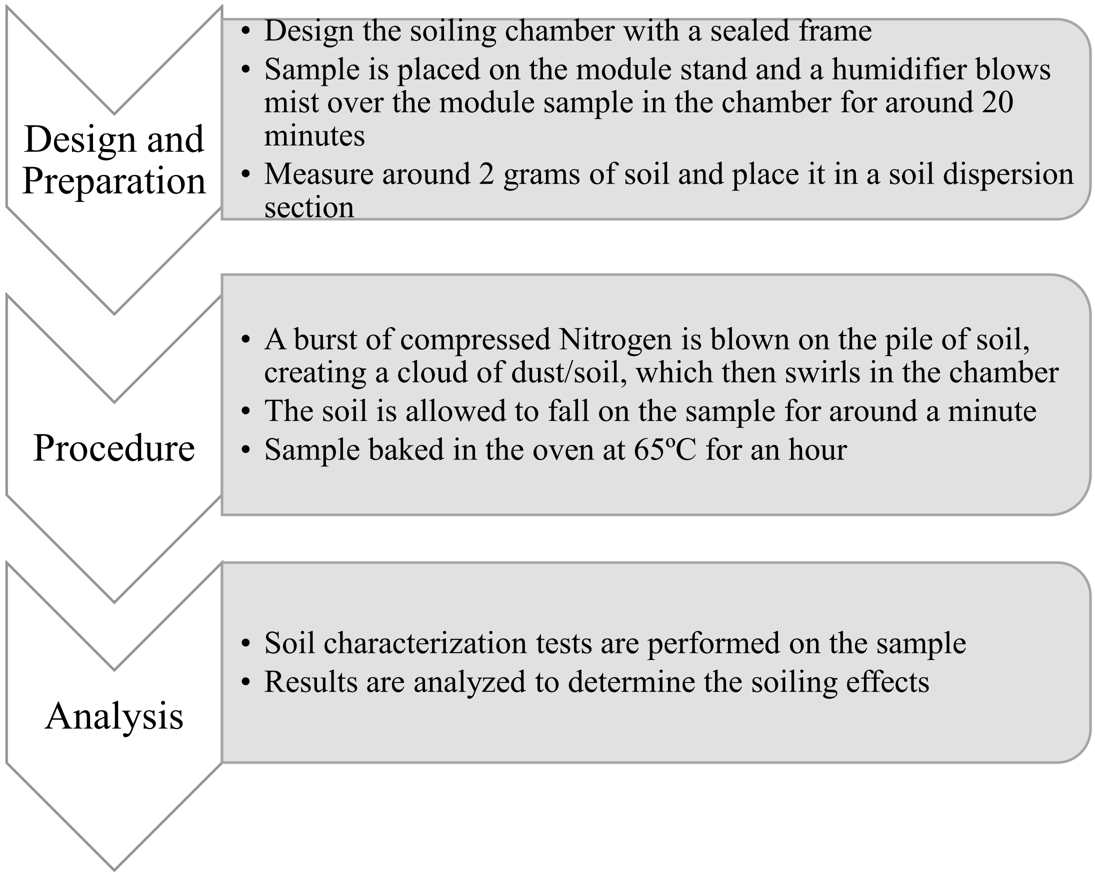
The characterization tests to be performed are:

- Reflectance on the mono crystalline cell
- QE on the module(before and after deposition)
- Short circuit current measurement of each individual cell
- IV for the module
- Particle Size Frequency and Soil composition
- Particle size distribution using optical microscope

These soil characterization tests were performed to determine the effects of the soiling layers on the performance and the specific wavelength range of the spectrum which would show the most amount of loss due to the soil layers. As this method replicates the dew cycles, comparing the characterization tests of the deposited sample with the naturally deposited soil, we can get an estimate on the acceleration factor of soil deposition for this setup.

3.1.3 Humidity Method

This technique is another way the replication of the moisture deposition on the sample surface can be visualized. This method can be summarized into the following steps:



In the soiling chamber designed at ASU-PRL, a few components are added onto the setup to facilitate the third type of soiling method. In this method, a humidifier is used to create a mist cloud over the module to create a film of water on the surface of the module. The difference of this method from the previous two methods is that, in this method, unlike before, the module is not kept inside the freezer to create the moisture condensation layer on its surface. The sample is simply placed on the stand inside the chamber and the humidifier is allowed to run for 15 minutes within the chamber. The humidity inside the chamber is then allowed to form a condensation layer on the glass surface. After 15 minutes, a measured quantity of soil (two grams) is placed in the soil chamber. Then, a burst of compressed Nitrogen gas is released onto the soil placed, creating a dust cloud. This dust cloud then mixes with the humidified air inside the chamber and by the effect of gravity slowly deposits onto the module. The deposition is allowed for around 1 minute. Then, the sample is taken out and kept in the oven for baking for an hour.

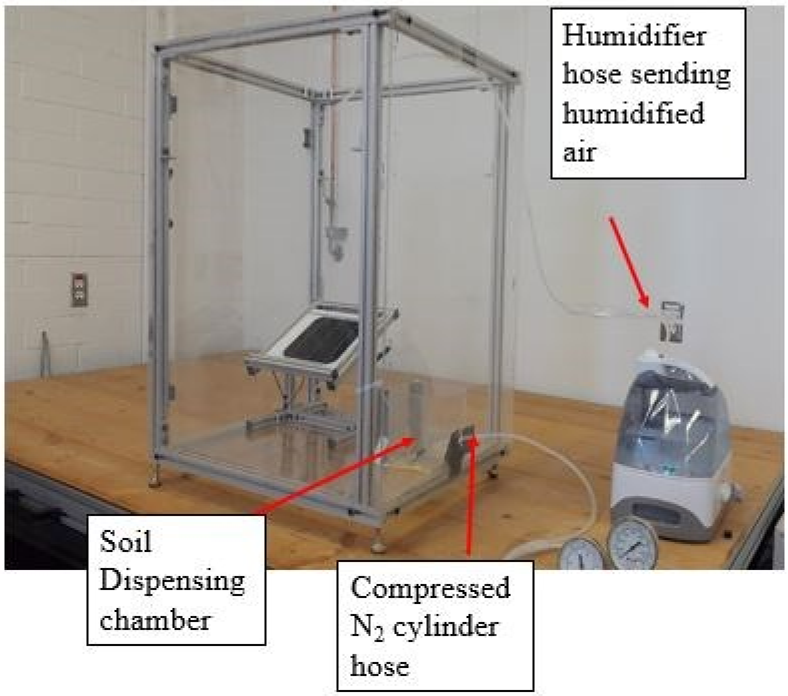


Figure 7: The Setup used for the Soil Deposition Method with a Humidifier (Humidity Method)

Depending on the number of cycles to be repeated on the sample, the steps are repeated. After all the steps have been completed, the sample is taken out and soil characterization tests are done on it. The characterization tests to be performed are:

- Reflectance on the mono crystalline cell
- QE on the module(before and after deposition)
- Short circuit current measurement of each individual cell
- IV for the module

- Particle Size Frequency and Soil composition
- Particle size distribution using optical microscope

As earlier, these soil characterization tests were performed to determine the effects of the soiling layers on the performance of the module and the specific wavelength region of the spectrum which would show the most amount of loss due to the soil layers. As this method also replicates the dew cycles, comparing the characterization tests of the deposited sample with the naturally deposited soil, we can get an estimate on the acceleration factor for this setup. This method can be a good simulation of the soiling prevalent in humid conditions.

3.2 Soil Collection

Collection of soil for deposition and characterization purposes is the first step which needs to be implemented. This dust is collected from the solar array field at Mesa, Arizona located at the premises of ASU-PRL. The dust collected off from the module surface kept in the field is used to be deposited on the coupon and the mini-module. As this dust has to be collected and kept uncontaminated, the collected soil is kept in a zip lock bag and scooped using a squeegee and brush. The bags are weighed before and after collection of soil using a high resolution weighing scale to determine amount of soil collected.

Figure 8: The Soil Collected in the Zip Lock Bag is Weighed (Image Source: ASU PRL)

Figure 9: The Soil Collected from the Surface of the Module Using Squeegee and Zip lock Bag

For the collection of the soil, a squeegee is used as shown in the figure. While collecting the soil from the module, care must be taken so that-

1) No particles other than soil is scooped up
2) Any bird droppings must be carefully avoided while the soil is collected
3) The amount of soil present on the module will be limited at best, hence care should be taken so that the soil is not spilled from the zip-lock bag
4) The soil constituent analysis requires only the analysis of the soil deposited on the module. Hence wearing a glove while handling the soil zip-lock bag is advisable

Figure 10: Collected Soil on the Left and the AZ Dust on the Right Used for the Experiments

The soil used for the experiments are shown in the figure above. The soil on the left is the collected soil from the module surfaces and the one on the right is the AZ dust. Visually, as can be seen, there is a distinct color difference in the two soil samples, which points at the different constituents of the soil. This distinct difference between the two soil types can be important in the characterization tests conducted on the soiled samples.

3.3 Soil Characterization

3.3.1 Reflectance on the Mono Crystalline Cell/ Coupon

Instrument used: Handheld FieldSpec 4 Wide-Res spectroradiometer from ASD Inc.

FieldSpec 4 Wide-Res spectroradiometer from ASD Inc. is a high resolution spectroradiometer which has been designed for a wide range of spectrum – (350 nm-2500 nm) which can in turn be put to use for a wide range of applications. The device allows the reflectance measurements accurately as the resolution of 8 nm meets the requirements of most hyperspectral sensors.

Reflectance is a basic test conducted across most PV testing laboratories which works on a simple principle. A lamp is present which acts as the light source for a region of the light spectrum. An optical fiber cable is then connected almost parallel to the light beam source whose purpose is to collect the reflected light and transfer it to the main processing unit of the machine. Before taking any measurements, the source needs to be optimized and calibrated to a white reference, which ideally just reflects all the light falling on it. Then the handheld transmitter-receiver is placed on a selected spot of the module and the measurements are taken.

Thus, the light emitted by the source becomes the signal and the received reflected signal becomes the received signal and depending on the signal, a curve is traced out showing which wavelength of light is reflected back the most. The machine can be tweaked so that the number of signals sent out for the source can be adjusted. This means, that for a particular spot, holding the lamp source steady, the number of times the machine sends out the signal and collects the reflected signal is adjusted [13]. Now the resulting graph should reflect the mean of the signals sent and received. Ideally, the graphs should just superimpose on top of each other.

For our experiment, we have taken the reflectance for the mini module at the same spot before and after soiling. This experiment is repeated for the Mono crystalline mini module, Poly crystalline mini module and the glass sample. In the case of the glass sample experiments, the glass sample is placed on a module at a particular orientation and the experiment is repeated at the same spot. The idea behind measuring the reflectance before and after soiling is very clear, to understand the reflection losses due to the soiling layers.

One point which needs to be highlighted is that once the measurements for the soiled sample is taken, the soil layers get disturbed and the soiling cycles need to be repeated all over again. In this thesis, care has been taken to make sure all the reflectance measurement are taken at the same spot, for the same sample over all the cycles for the different soil types involved in the measurement.

Figure 11: The FieldSpec 4 Reflectance Machine with the Optical Fiber Cable (Image Source: ASU PRL)

3.3.2 QE on the Module

Instrument used: PV Measurements QEX12M

The basic concept of the QE machine is to pass through a known amount of photons into the module to measure the electrons coming out into the circuit. To achieve this, the sample used is masked completely. In our case, as the sample is a single cell mono crystalline coupon, we need to mask the same with a masking tape and black foam with a single slit present to allow a single beam of laser to fall on the cell [14]. The coupon can be directly connected to the QE machine and the procedure for measuring the QE be followed accordingly. Firstly, the QE machine needs to be calibrated as per the standard and the laser beam is moved using the controls to get the laser beam directly on the exposed cell. The next step is to cover the cell with a shroud which basically doesn't allow any residual light to pass through.

Figure 12: The PV Measurements QEX12M Machine Used to Measure the QE for the Samples- Before and After Soiling (Image Source:ASU-PRL)

For this thesis, we will discuss only the results of the Mono-Si coupon for their reliability and ease of measurements. As mentioned, the QE machine is first calibrated as per the instructions of the machine manual. Then the shroud head of the machine is moved such that the laser falls directly on the cell surface of the coupon through the hole made in the cover to block the light to the rest of the cell. QE works on the principle that all other light source to the module is blocked except for the laser light which is a measured quantity in the machine processor. Then a shroud head covers the cell section such that only light available is the laser light. Then the measurements are taken and the machine basically detects the amount of electrons sent into the machine circuit because of the incident light falling on the module. An internal processing gives the curve as the output for the QE test. This test is taken before and after soiling to again quantify the amount of losses seen due to soiling.

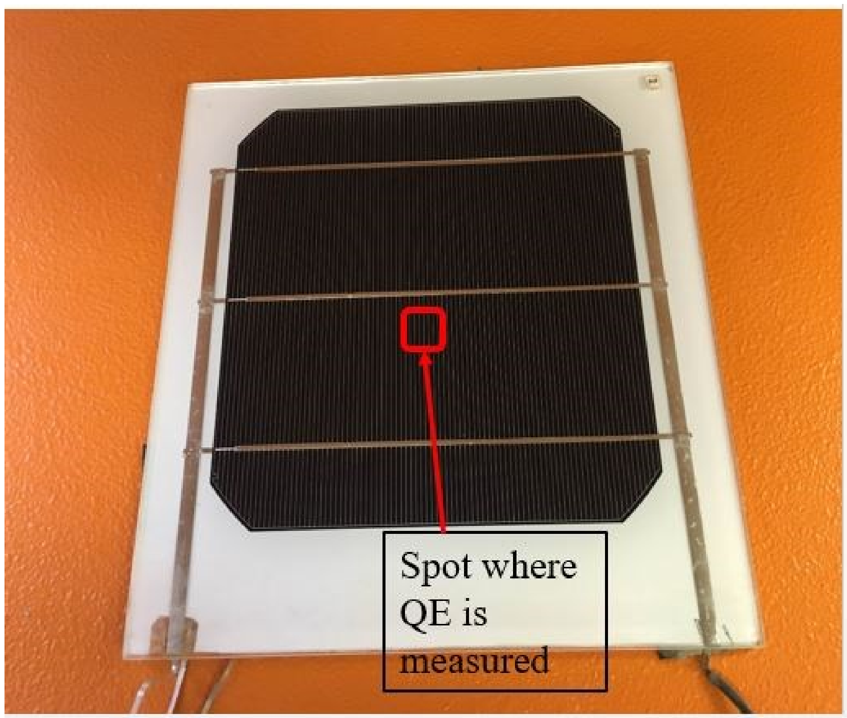


Figure 13: Spot Showing where the QE is Measured Before and After Soiling

An important step in this experiment is the calibration of the QE machine. The calibration of the QE machine needs to be done carefully as the LEDs responsible for sending the signal light for the wavelength range of the spectrum need to be carefully handled. The results seen for the samples have been discussed more in detail in chapter 4.

The results from the QE machine can be a very good indication of the soil uniformity as the variation of the soiled samples from the standard, clean samples can show a consistency in the experiment. Thus the repeatability of the procedure can be verified using the results of this technique.

3.3.3 Short Circuit Current (Isc) Measurement

Instrument used: PV Measurements Indoor Solar simulator

One of the most important factors used to determine the losses due to soiling is the short circuit current (I_{sc}). The instrument used to measure the Isc values for each cell of a module is the Indoor Solar simulator.

The solar simulator works on the principle of sending a beam of xenon lamp light in the spectrum range ideal for replicating the solar beam irradiance. For the experiment, the instrument is first calibrated using a reference cell and using a simple Fluke Multimeter. Then the sample is kept in place of the reference cell and the measurements are taken before and after soiling. In case of the glass sample, the glass sample, the sample is simply placed over reference cell to check the relative reduction of measured value before and after soiling.

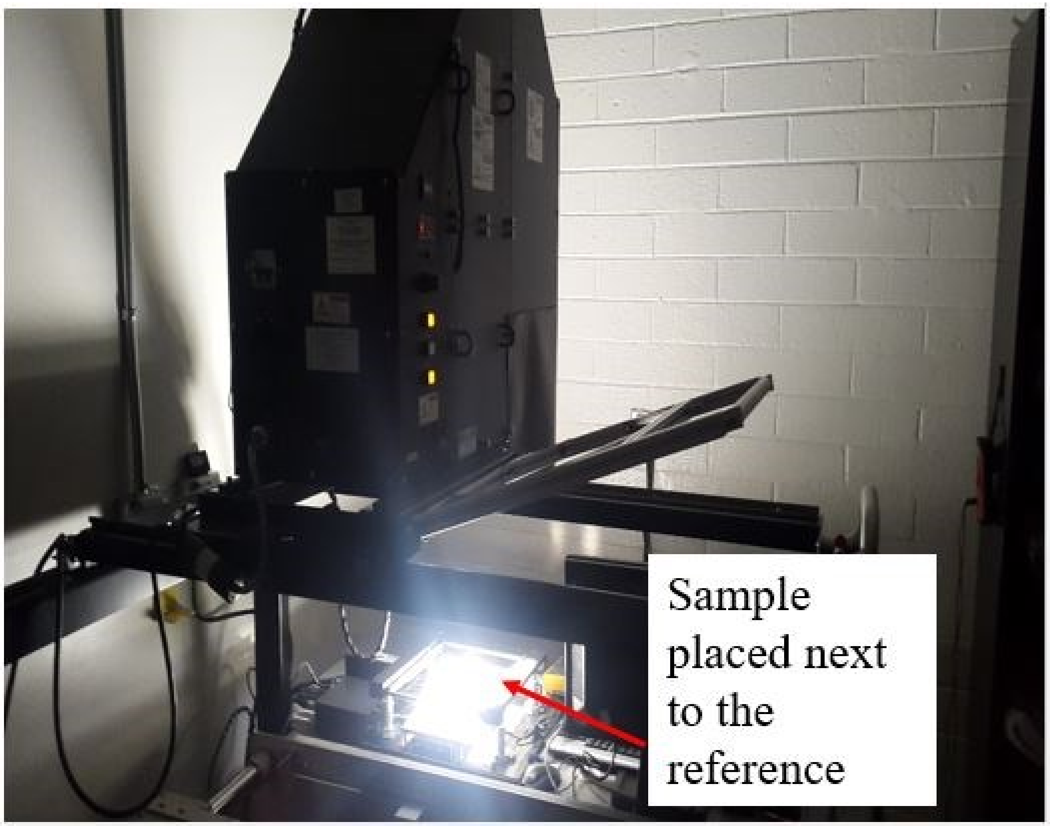


Figure 14: PV Measurements Solar Simulator Setup Used to Measure the Isc Value

While taking the measurements for the I_{sc} values for each cell, care must be taken that while connecting the soldered wires to the connectors of the solar simulator, the soil deposited shouldn't be disturbed or touched. Also, the soldered wires for each of the adjoining cells should be kept separate while measuring to make sure that the short circuit current (I_{sc}) is measured only for that cell. The nature of the results obtained for the I_{sc} measurements will be the primary candidate verifying the uniformity of the soil deposition. The difference in the measured values for the clean and the soiled samples should stay consistent for each of the cell for a constant irradiance, assuming other factors are constant. The slight variations seen in the measured values must be within an acceptable error range to be accepted.

3.3.4 Current-voltage for the Module

Instrument used: Daystar IV curve tracer

The current-voltage (IV) characterization of the modules used for the experiment are measured using the Daystar IV curve tracer before and after soiling. The solar simulator has a limitation in terms of measuring values of a module above 7 Volts. As such, to check the overall characterization of the whole module, we use the module level curve tracer.

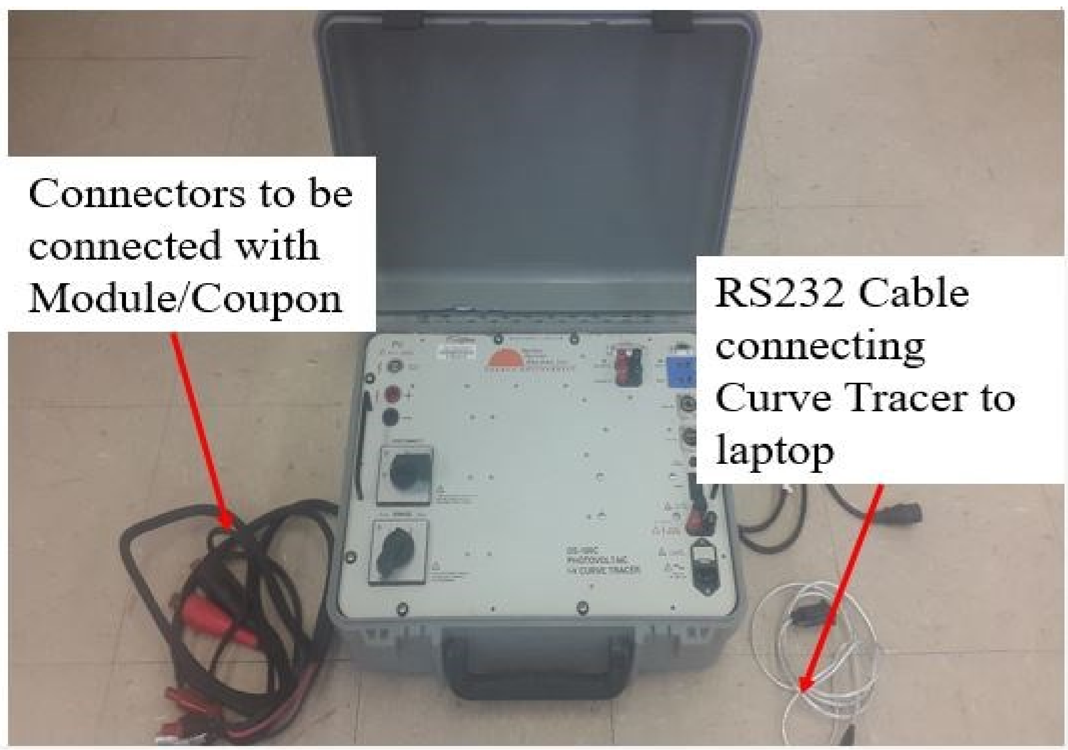


Figure 15: The Daystar IV Curve Tracer to Measure the Current-Voltage Curves (Image Source: ASU PRL)

For the glass sample, we first take the curve using a reference cell and then take the curves by placing the clean glass sample and then the soiled glass sample on it. This basically indicates the amount of transmittance loss due to the deposited soil on the glass sample.

The Daystar IV curve tracer is used to measure the short circuit current values for the whole module to verify the trend as expected due to increasing soiling. As in the case of the Indoor solar simulator, care needed to be taken while taking the IV measurements so that the soil layers don't get disturbed.

3.3.5 Particle Size Distribution Using Surface Imaging

Instrument used: ZeScope optical microscope

The soiled samples were taken to Leroy Eyring Centre for Solid State Science at the ASU Tempe campus to study the layers of the soil deposited on the sample. Using a ZeScope optical microscope, the particle count for the soiling cycles was determined.

The ZeScope optical profilometer has two beam splitters in its optical housing. The first beam splitter splits the original laser light source into two halves. One half falls on a reference mirror inside the optical housing of the profilometer. The other half is sent to fall through the focus of an objective lens. When the light beam is made to fall on a test surface, the instrument is adjusted such that the distance of the reference mirror from the first beam splitter is equal to the distance of the test sample from the second beam splitter. The instrument now detects the reflected light from the test sample and the two light beams meet to cause interference. As a result of the constructive and the destructive interference between the two light beams, the height of the test sample can be measured.

This is then repeated for the whole range of the sample section and a ‘surface image’ can be produced for easy viewing.

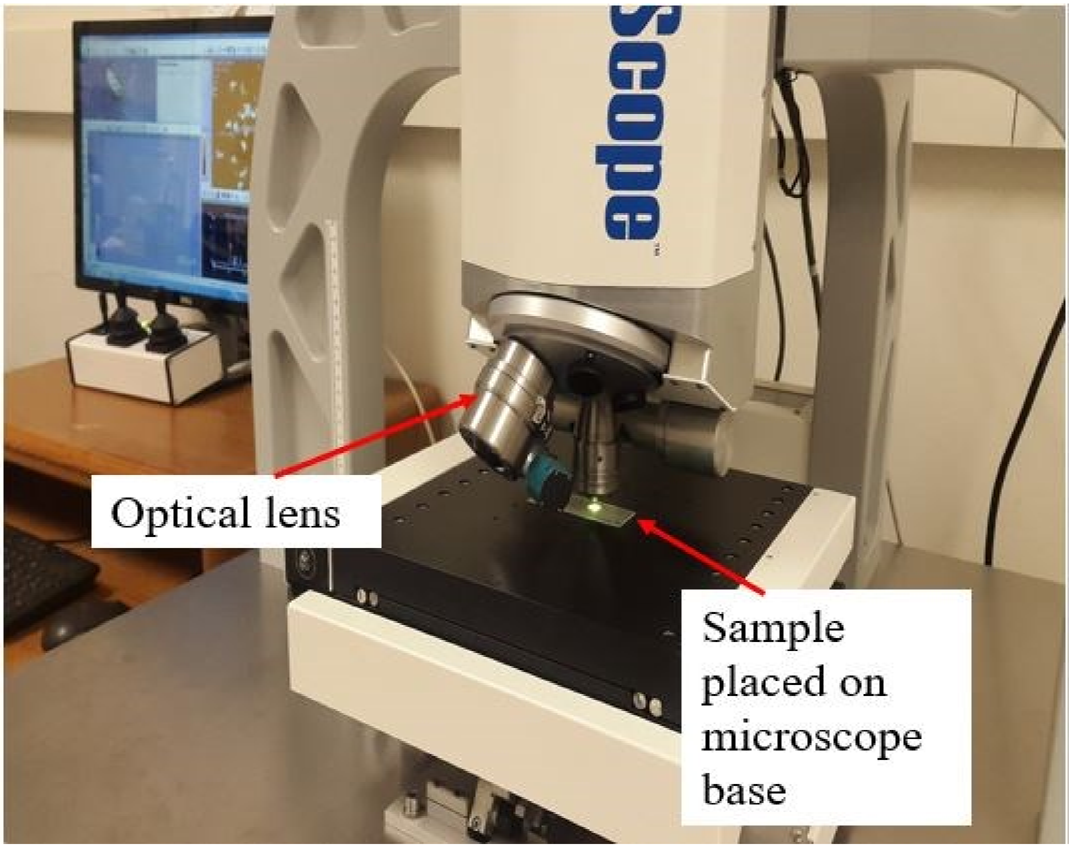


Figure 16: The ZeScope Optical Microscope Setup (Image Source: LeRoy Eyring Center for Solid State Science)

For conducting the experiment, the following steps are followed. The instrument consists of a plate which acts as the base for keeping the sample. Before the sample can be analyzed, the base is first taken to a homing position. The equipment then proceeds to go through a series of steps to focus on the sample and the soil deposited on it. It uses a laser which is then zoomed so that the focus is just right on the soil sample. Once the image is brought to focus and is set, a section of the sample is taken whose images are then taken and stitched together to give a 3d rendition of the soil deposited. The image is then to be studied using the ZeScope software to analyze the soil particle distribution and the best contrast needed to view the particles.

Depending on the results obtained, the focus of the microscope should be adjusted to get a better image for processing. The setup needs to be handled with care as the instrument is sensitive to any external force. Also the values entered as the parameters of the samples need to be fairly accurate. For example, if the samples measured had a thickness of 3mm, the parameter for the width in the ZeScope program needs to be entered as the same.

3.3.6 Particle Size Frequency and Soil Composition

The results obtained from NREL comprise of the Scanning electron microscope (SEM) analysis of the collected soil deposited on the glass samples and the transmittance capacities through the soiled sample. The results from the SEM analysis would reveal the soil composition, which is the constituents of the soil collected from the module surface at ASU PRL.

The soil constituents would give an idea of the components which could cause a particular effect on the transmission losses for the soiled samples. Also it would help understand if a particular cleaning approach would be better than some other industrial cleaning approaches. The climatic conditions will have an effect on the type of soil in a particular location. As such, the chemistry of the adhesiveness of the soil type on the glass sample will also depend on the type of environment it is deposited under. The comparative studies of the SEM analysis for different soil types will be effective in understanding the effects of the same on the soil deposition.

4.0 RESULTS AND DISCUSSION

For this thesis, to collect a good range of data accurately, the same sample coupon was soiled using the dry, dew and the humid methods. To understand the effects of each changed variable on the outcome of the experiments, the results of the experiments conducted on the soiled samples are analyzed and discussed below.

In the case of the dry method of soil deposition, it could be seen that the soil deposition pattern was non-uniform. This could be attributed to the clumps formed in the soil due to big mesh size and the irregularity caused due to the manual vibrational system. Hence the I_{sc} measurements for the sample returned sporadic and random values indicating that the soil deposition is non uniform. So, we shall not look at the soil characterization results for the dry method.

4.1 Short-circuit Current (Isc) Measurement

For this thesis, let us now look upon the Isc results according to the other two methods of soil deposition used. The first method we will look at is the 'dew' method. Also, we shall look into the results for the coupon based on the soil deposited. The chart below shows the results of the measured Isc for collected soil deposited on the coupon using the dew method for a sequence of sampling.

As seen in Figure below, the chart signifies that as the soiling intensity increases, the Isc value drops. In this case, the soil deposited is the collected soil from the module surface on the ASU PRL solar field at Mesa, Arizona. Observing the soiled sample visually, we can say that the collected soil is very fine and uniformly spreads across the sample.

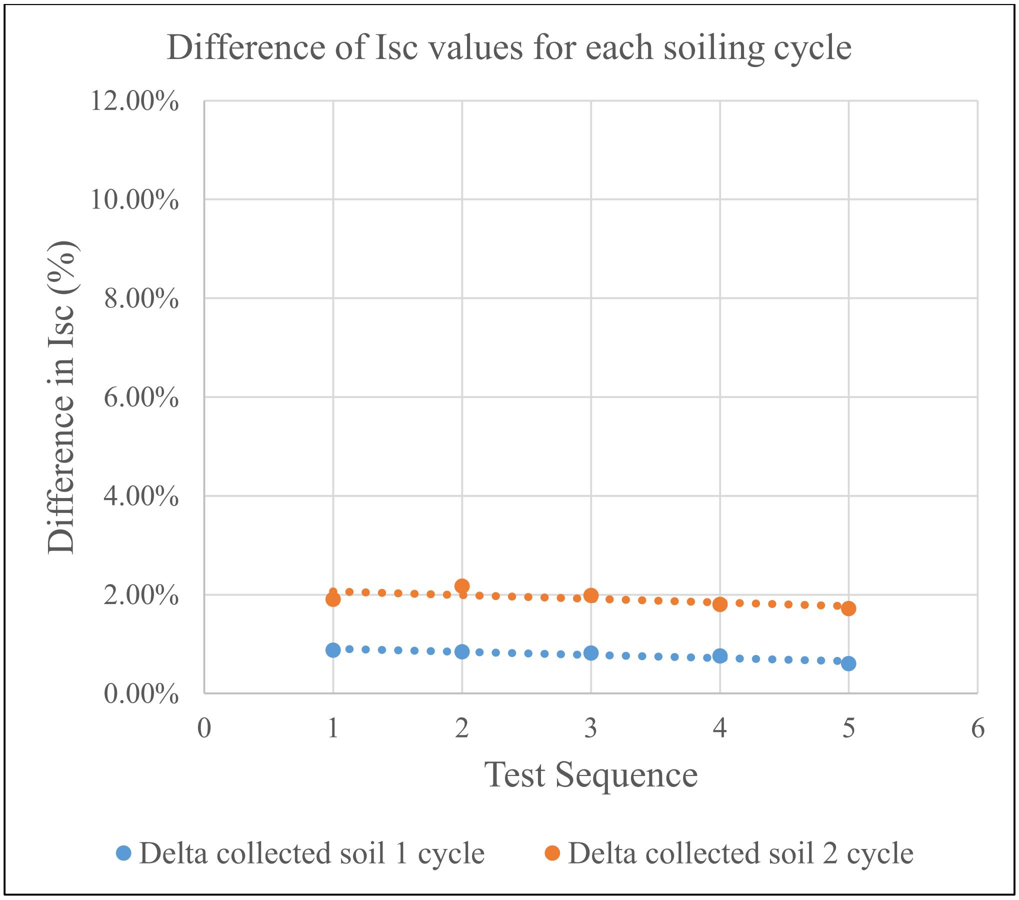


Figure 17: Isc For Collected Soil On Coupon- Dew Method Of Soil Deposition Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Of Settling Time To Achieve Soil Density Of Approximately 1.4 g/m2 per cycle

The trend in Figure 17 shows that the difference in the measured values for the same coupon when measured for the clean phase, soiled for one cycle phase and soiled for two cycles phase shows that it remains consistent across the sampling sequence. The average losses seen for the consecutive soiling cycles is around 0.77% and 1.91%. The almost constant variation in the Isc values from one cycle to another points towards uniform soil deposition. However the slight drop in the Isc values shows that the soil deposition intensity is less, while being uniform.

Next, we look at the same method of soil deposition but this time, we use the standard, commercially available AZ test dust. The following chart shows the AZ dust deposited on the Coupon by the dew deposition method.

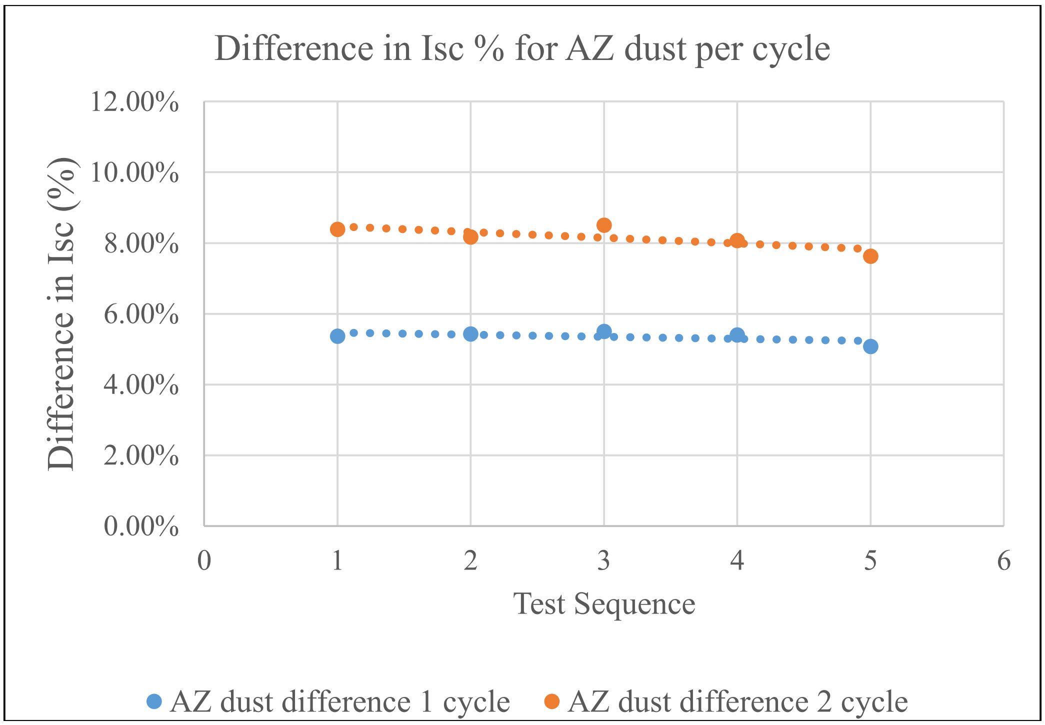


Figure 18: Isc For Collected Soil On Coupon- Dew Method Of Soil Deposition Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Of Settling Time To Achieve Soil Density Of Approximately 1.4 g/m2 per cycle

Similar to that seen for the collected soil, the AZ dust samples also show a decrease in the values of Isc with increasing soiling intensity. Also the Isc values measured show that the difference between the clean phase and the subsequent soiled phases are pretty consistent, thus proving that the module is uniformly soiled. This is also an indication at the repeatability of the soil deposition method. Furthermore, visually inspecting the coupon sample, we see that the AZ dust seems to have a uniform spread across the sample too but slight clumping is seen on the AZ dust sample. This is attributed to the possible moisture seeping into the AZ dust container which causes the creation of clumps in the spread on the sample.

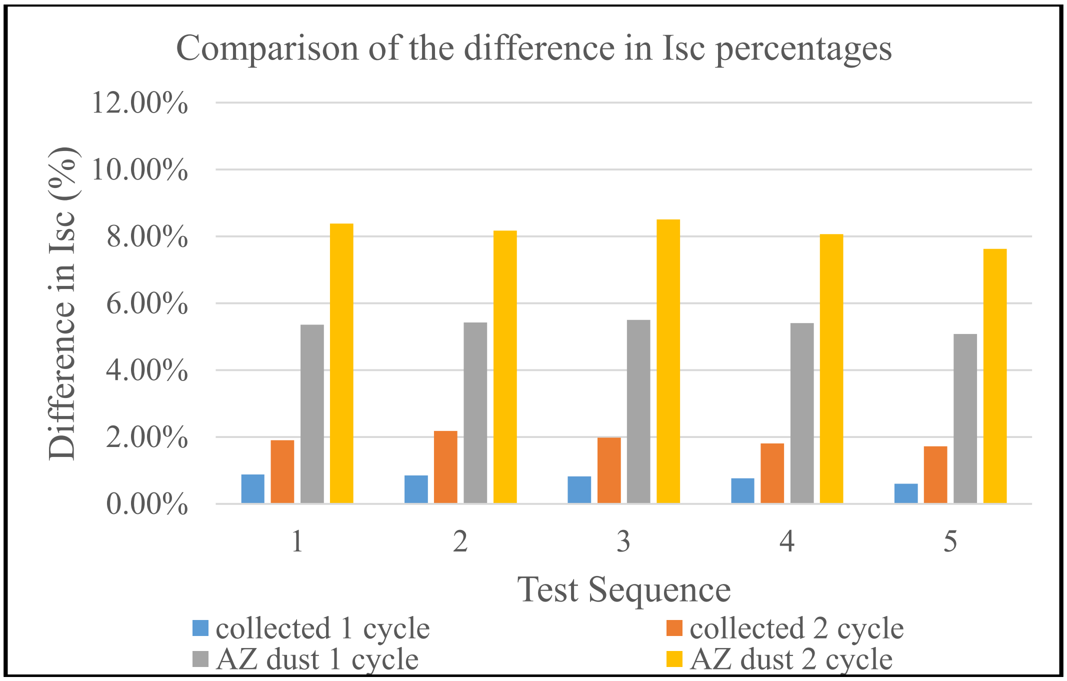


Figure 19: Comparison Of The I_{sc} Drop For AZ Dust And Collected Soil- Approximately 2 Grams Of Soil Placed In The Soil Dispersion Chamber And Around 1 Minute Of Settling Time With Soil Density Of Around 1.5 g/m^2 per cycle

As expected and seen earlier, the Isc is seen to drop as the soiling increase. But the interesting thing to note is that the AZ dust is seen to cause a higher loss in Isc as compared to the collected soil. A hypothesis can be made at this instant that the size of the particles for the AZ dust is more than that of the collected soil leading to higher current losses. As current produced by the cell is directly proportional to the irradiation, we can say that the AZ dust allows lesser wavelengths of light to pass through. Either it absorbs more of the wavelengths or it reflects/scatters more wavelengths of white light back towards the source. Plotting the trend lines along with the data shows an almost linear trend in the Isc measurement which shows there is a consistent drop of Isc across the samples. This variation in soiling loss is evident only after changing one variable in the soil deposition method. The higher soiling intensity of the AZ dust could potentially mean that using that dust for accelerated testing methods will have a higher accelerated soiling rate as compared to the soil collected at Mesa, Arizona.

4.2 Surface Imaging

The surface imaging is done using the ZeScope profilometer and it showcases the microscopic image of the soiled samples. In the first image below, we see a sample with 5 cycles of AZ dust deposited on it. A microscopic count of the dust particles revealed 1670 particles in a 1000 µm side square on the surface of the module.

The 3d imaging analysis of the ZeScope profilometer is dependent on the parameters of the sample being given correctly. As such, the height of the sample and the focus parameters used for focusing the image is very important. As is seen in the figure, the 5 cycle deposition leads to a deposition of AZ dust with some clumps of soil across the surface. These clusters of soil particles can be attributed to the higher moisture content in the AZ dust container leading to stickier and coarser particles on the sample surface. As can be seen from the 3d image, the peaks of the soil deposited varies due to variations in size and effects of gravity.

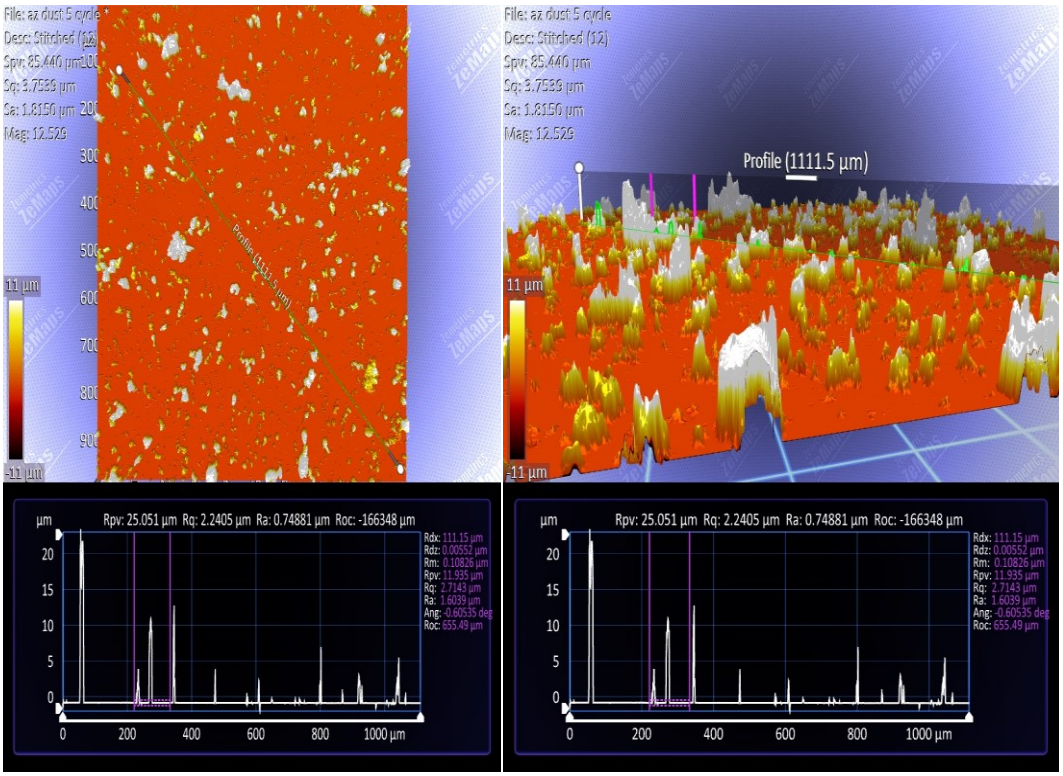


Figure 20: Surface Image Of AZ Dust 5 Cycle Sample- Approximately 2 Grams Of Sample Soil Kept In Soil Dispersion Chamber And Approximately 1 Minute Of Settling Time With Soil Density Of Around 1.4 g/m^2 per cycle

The particle count for the AZ dust deposition for the 5 cycle deposited sample is around 1760 particles within the observed section. This count is expected to go up for subsequent soiling cycles. This gives an indication that the increase in the number of soiling cycles will lead to an increase in the uniform deposition of the soil.

The following images shows the collected soil deposited on a sample using the NREL method of deposition. To have a good idea of the soiling effects, we have performed surface imaging on the samples for 2 cycles, 5 cycles and 7 cycles of soil cycles.

The image shown below is the surface image of a 2 cycle collected Mesa deposited soil using the Dew method. As we look at the image, we can see that the particle count is around 760 particles for a 1000µm side square. Here, comparing the image to the earlier image of AZ dust deposition, we notice a visible less amount of soil particles, but this can be attributed to the number of soiling cycles which the samples are subjected to. Looking at the profile drawn for this sample we find a number of peaks and see a random scattering of big and small particles across the sample section. The scale shows the variation of the height of the soil particles with respect to the glass surface.

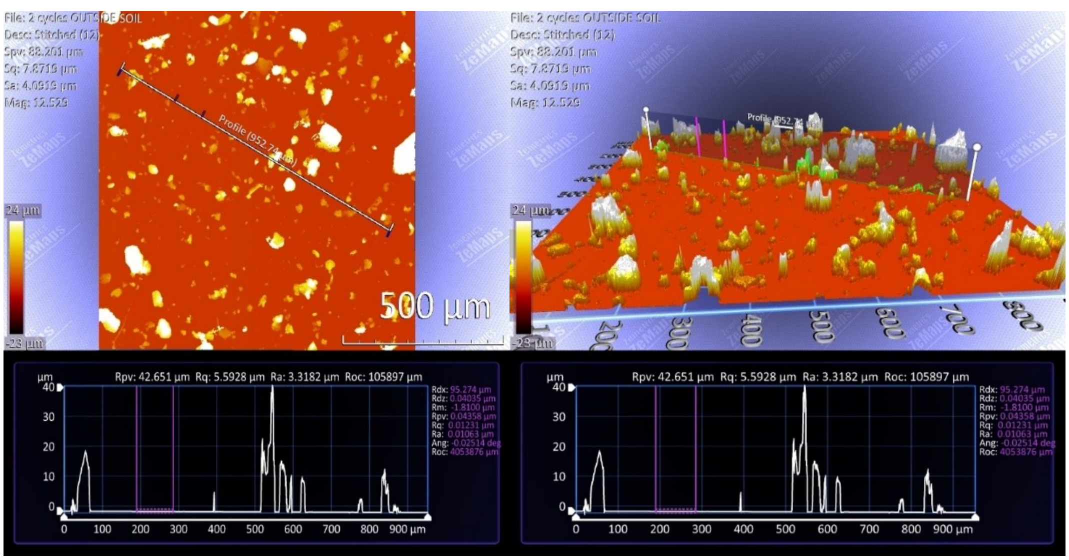


Figure 21: Surface Image Of Mesa Collected Soil 2 Cycle Sample- Approximately 2 Grams Of Sample Soil Kept In Soil Dispersion Chamber And Approximately 1 Minute Of Settling Time With Soil Density Of Around 1.4 g/m2 per cycle

Now we look at the surface image for the sample for 5 cycles of collected soil deposited on the sample. The figure shows the sample after being subjected to 5 cycles of freezing and soiling. We find that the samples show a particle count of around 1350 for a 1000 µm side square. Here, for this sample, we see that the sample will have a higher number of soil particles as compared to the 2 cycle deposition. Also we see a relatively higher number of soil particles which is a direct result of the higher number of soiling cycles.

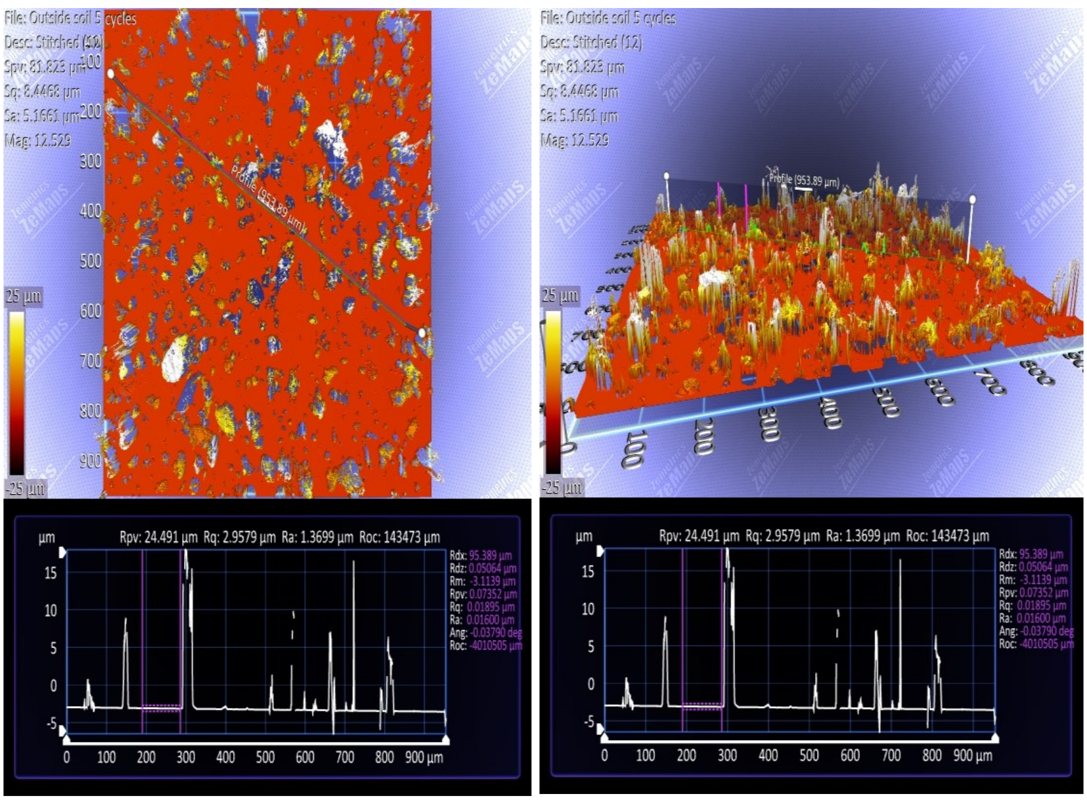


Figure 22 Surface Image Of Mesa Collected Soil 5 Cycle Sample- Approximately 2 Grams Of Sample Soil Kept In Soil Dispersion Chamber And Approximately 1 Minute Of Settling Time With Soil Density Of Around 1.4 g/m2 per cycle

The following figure shows the surface imaging for a sample subjected to 7 cycles of soiling of collected soil by the NREL method.

The sample is seen to have around 1790 particles for 1000µm side square. As expected, we see an increase in the soil particles with an increase in the soiling cycles leading to more reflection/absorption of irradiance falling on the sample. For the sample given here, the number of particles is more than that seen for the 2 cycle and 5 cycle samples. Also we see that there is a noticeable decrease in the amount of free space of the glass sample.

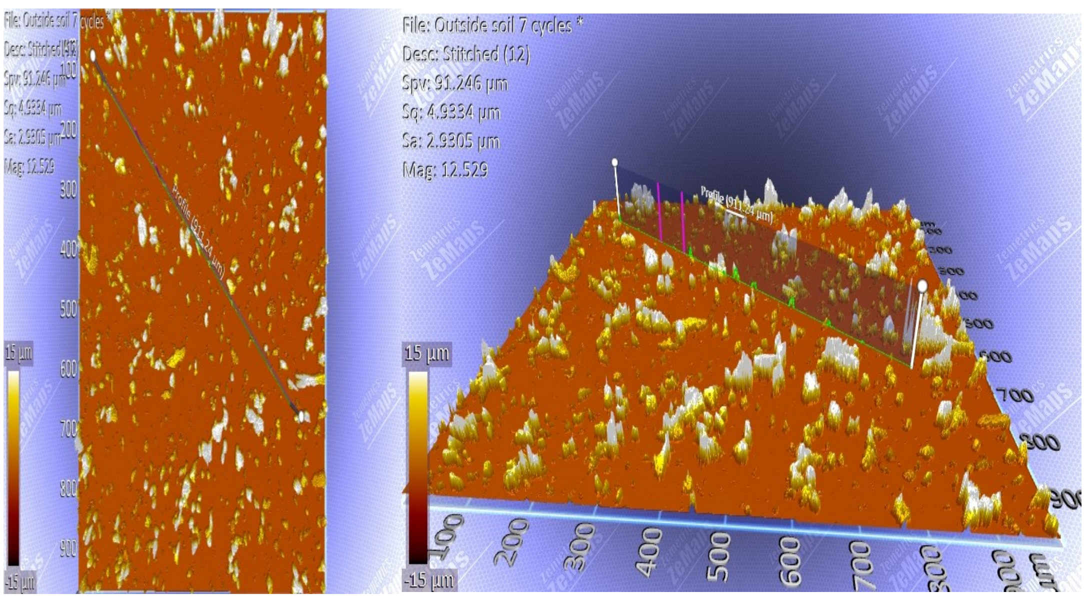


Figure 23: Surface Image Of Mesa Collected Soil 7 Cycle Sample- Approximately 2 Grams Of Sample Soil Kept In Soil Dispersion Chamber And Approximately 1 Minute Of Settling Time With Soil Density Of Around 1.4 g/m2 per cycle

The samples show a trend which is interesting to note. We can thus verify that the soil uniformity depends on the number of cycles of deposition. As is seen in the modules installed outside, the soil deposition becomes more and more dense and uniform with increasing number of installed non-cleaning days. This is because with more number of passing days, more dust particles suspended in the air get deposited on the module surface, and by the adhesive nature of one dust layer over the other helps in depositing more number of soil layers.

4.3 Quantum Efficiency (QE) Measurements

The QE measurements are taken for the coupon for AZ dust initially after two cycles of soiling.

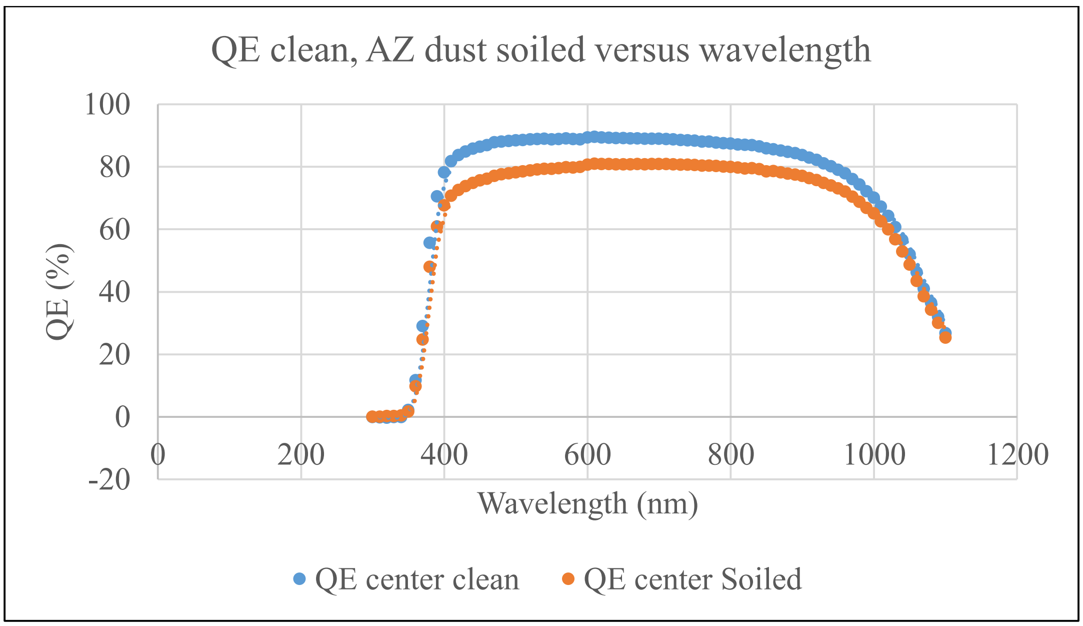


Figure 24: Sample Soiled With AZ Dust For 2 Cycles by the Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber & Approximately 1 Minute Settling Time & Around 1.45 g/m^2 soil deposition per cycle

As seen in the Figure 24, the QE curves values go down after soiling as expected. As the QE is a representation of how much irradiance is allowed to pass through, this shows that the soiling leads to a decrease in the amount of light passing through. This decrement shows that the soil is acting more like a neutral filter only reducing the intensity of the irradiation. Also the difference of the QE values for the soiled sample as compared to the clean sample shows that there is an increase in the QE values below 1100 nm upto 300 nm where there is a sudden drop in the values. This is in line with what is expected as the bandgap of the semiconductor (in this case Silicon) falls within that range of wavelength spectrum.

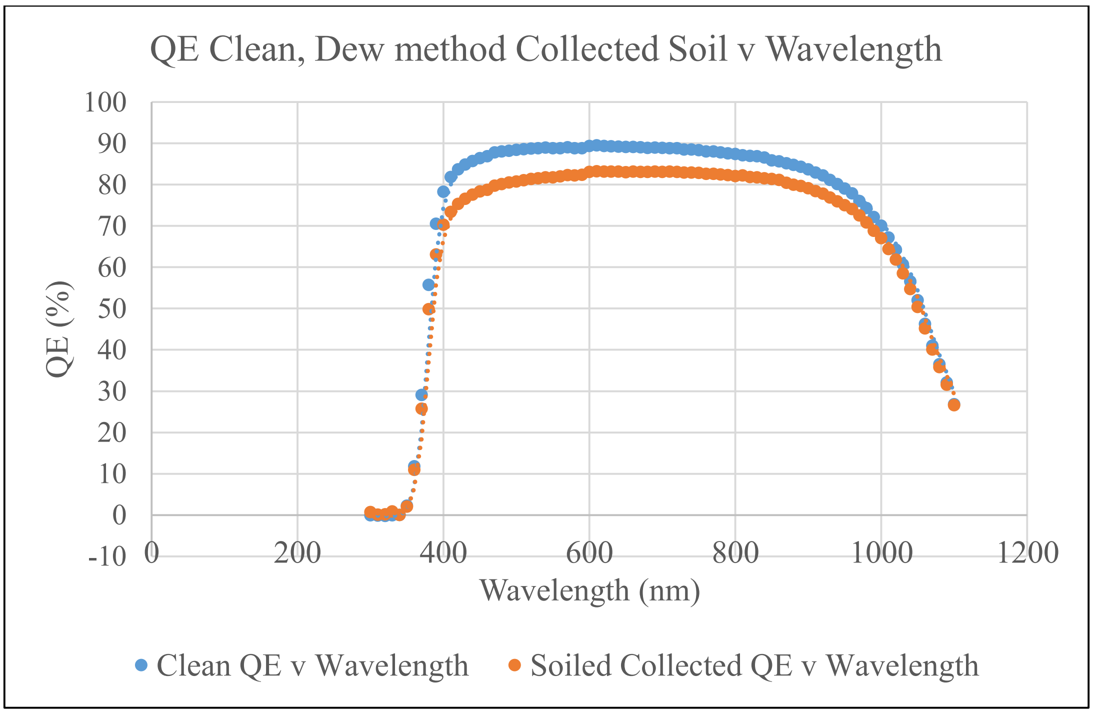


Figure 25: Sample Soiled With Collected Soil For 2 Cycles By The Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approximately 1.45 g/m2 soil deposition per cycle

The Figure 25 shows the QE curve for a soiled Coupon with collected soil using Dew soiling method. There is a distinct decrease in the transmittance values as seen.

Another important thing that can be noted is that the values for the soiled coupon are much higher than the soiled values of the AZ dust soiled coupon.

The Figure 26 here below shows us the QE measured graph for a comparison of the AZ dust and collected soil for the Dew method as seen below.

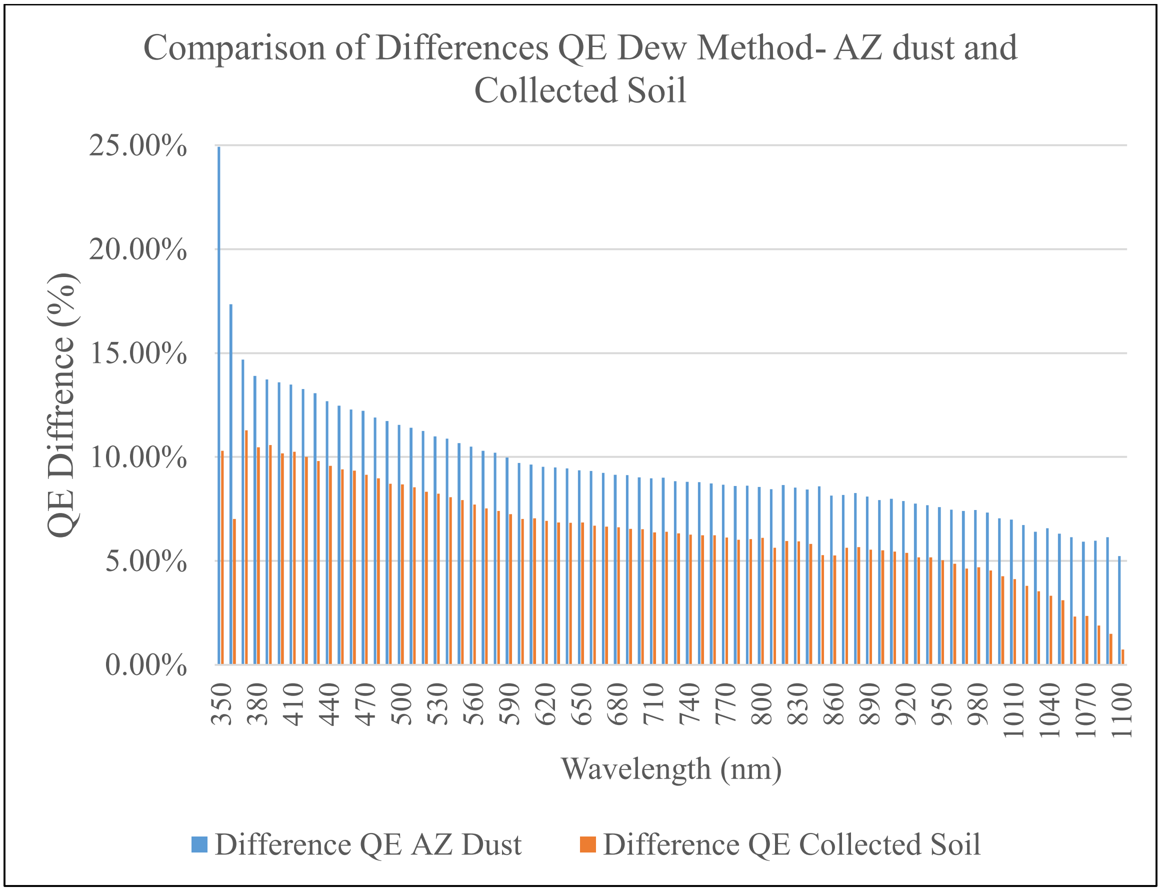


Figure 26: Sample Soiled Comparing AZ Dust And Collected Soil For 2 Cycles By The Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 g/m2 soil deposition per cycle

The Figure 26 clearly shows that the AZ dust measured QE difference is higher than the collected soil measured QE difference with respect to the clean coupon, indicating that the AZ dust doesn't allow irradiance to pass through due to the coarser size and clumps formed. Since the QE measurements shows which wavelength of light is transmitted across the soiling layer onto the PV coupon, the higher drop of QE values for the AZ dust shows a higher soiling intensity, thus pointing out that for the same conditions of soil deposition, the type of soil will affect the soil deposition and the intensity.

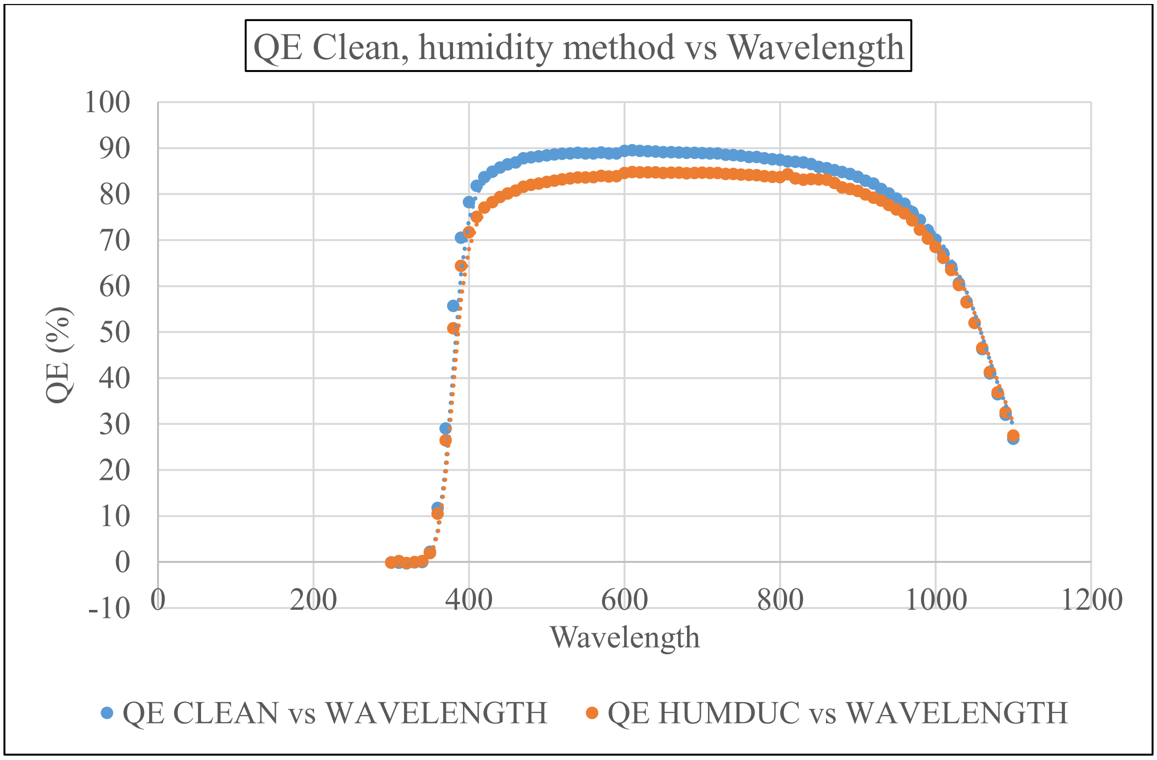


Figure 27: Sample Soiled With AZ Dust For 2 Cycles By The Humidity Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.48 g/m2 soil deposition per cycle

The Figure 27 above shows the QE measurements for a Coupon soiled for two cycles using AZ dust with the humidity method. The QE values follow the expected trend of losses in QE values with increase in soiling. The QE values for the clean Coupon can be seen to be higher than the soiled Coupon showing the losses in the signal wavelength due to the incident light being blocked by the soil particles.

The Figure 28 below shows the QE measurements for a coupon with collected soil deposited using the humidity method.

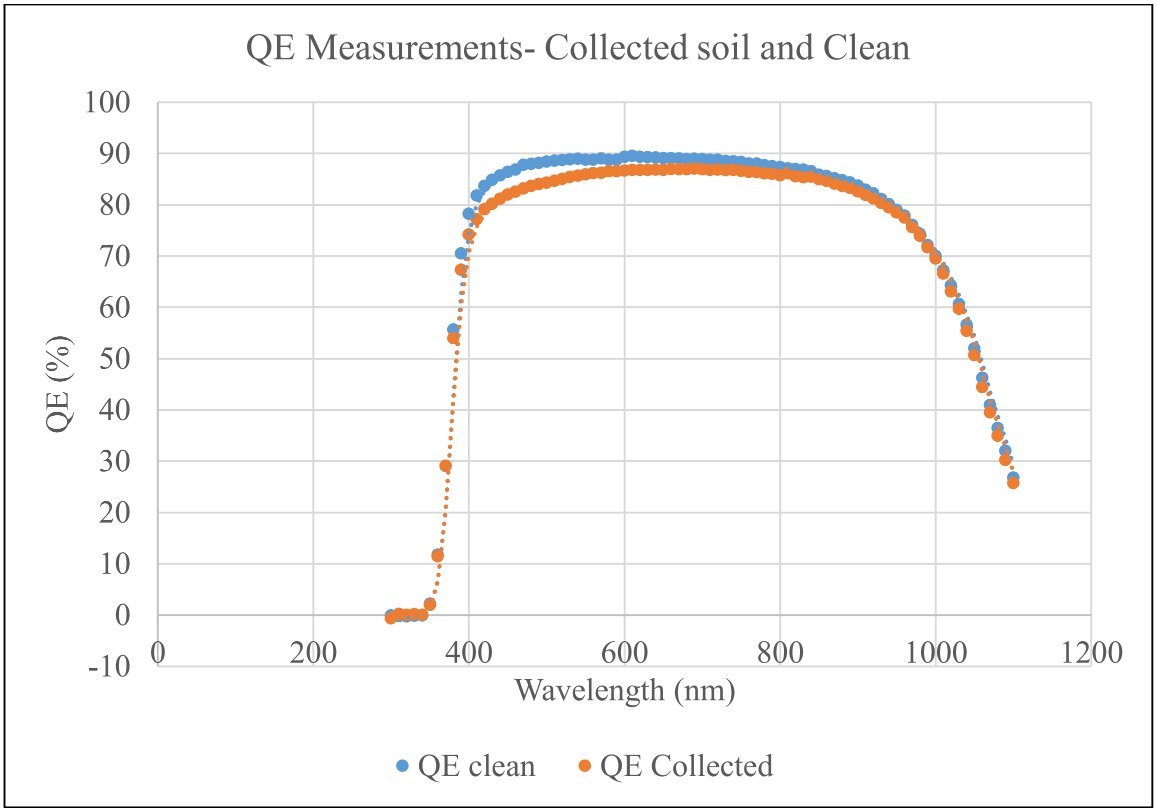


Figure 28: Sample Soiled With Collected Soil For 2 Cycles By The Humidity Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approximately 1.48 g/m2 soil deposition per cycle

As seen above, the QE for the measured coupon shows an expected trend of lowered QE values with increase in soiling. This chart again shows the characteristic drop in Isc values due to the soil particles blocking the incident light.

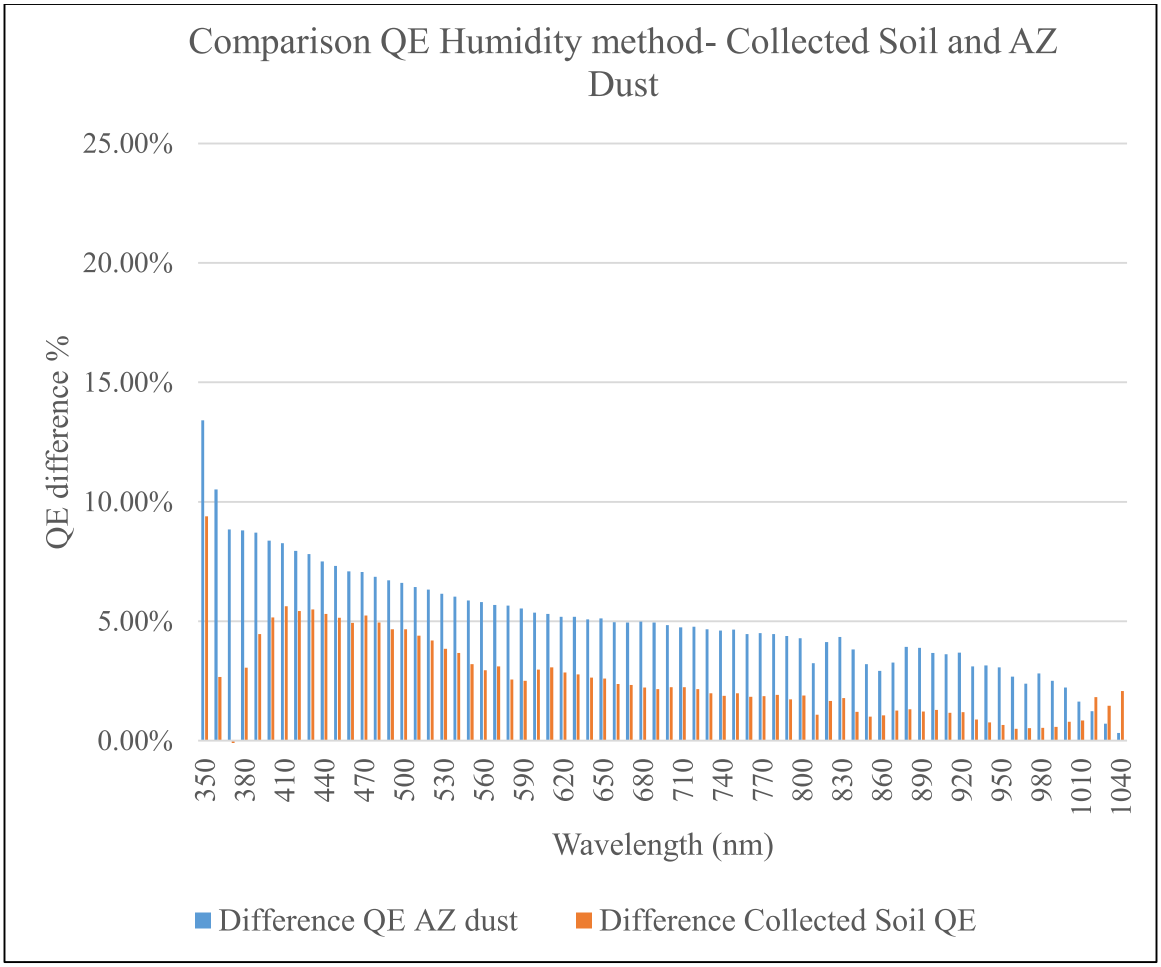


Figure 29: Sample Soiled Comparing AZ Dust And Collected Soil For 2 Cycles By The Humidity Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 g/m2 soil deposition per cycle

The Figure 29 above shows the QE difference measurements for the deposition of AZ dust and collected soil using humidity method of soil deposition. As such we can clearly make out that the AZ dust deposition is more inclined to cause losses in QE as compared to collected soil due to the clumps and coarser soil particle size. This is evident by the higher losses for the AZ dust as compared to the collected soil.

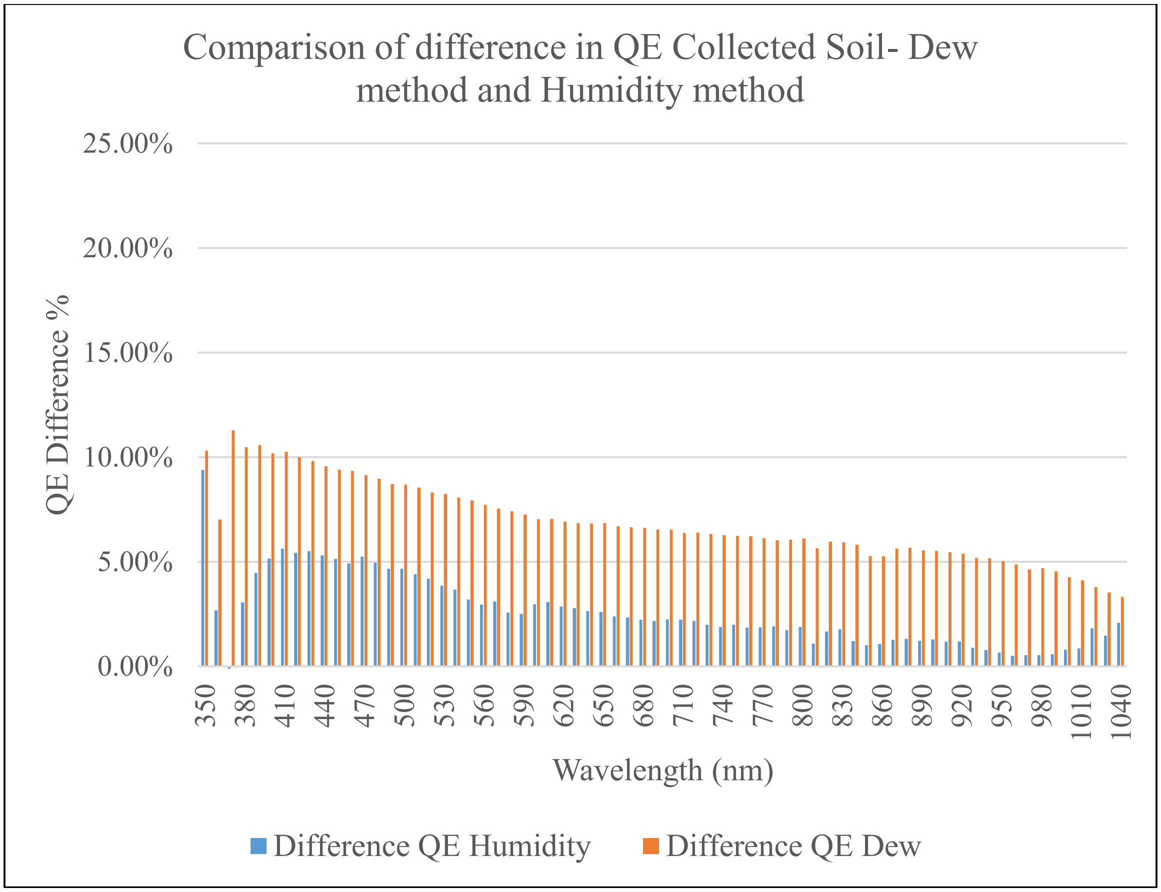


Figure 30: Sample Soiled Comparing Collected Soil For 2 Cycles By The Humidity And Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 g/m2 soil deposition per cycle

The Figure 30 above shows that the dew method of soil deposition causes more QE losses as compared to the humidity method of soil deposition. This could be attributed to the higher cementation of soil in the dew method due to the direct condensation of moisture on the coupon surface upon taking out from the freezer as opposed to the indirect condensation of moisture due to the humidity method. The QE results show a scattering towards the higher end of the wavelength spectrum.

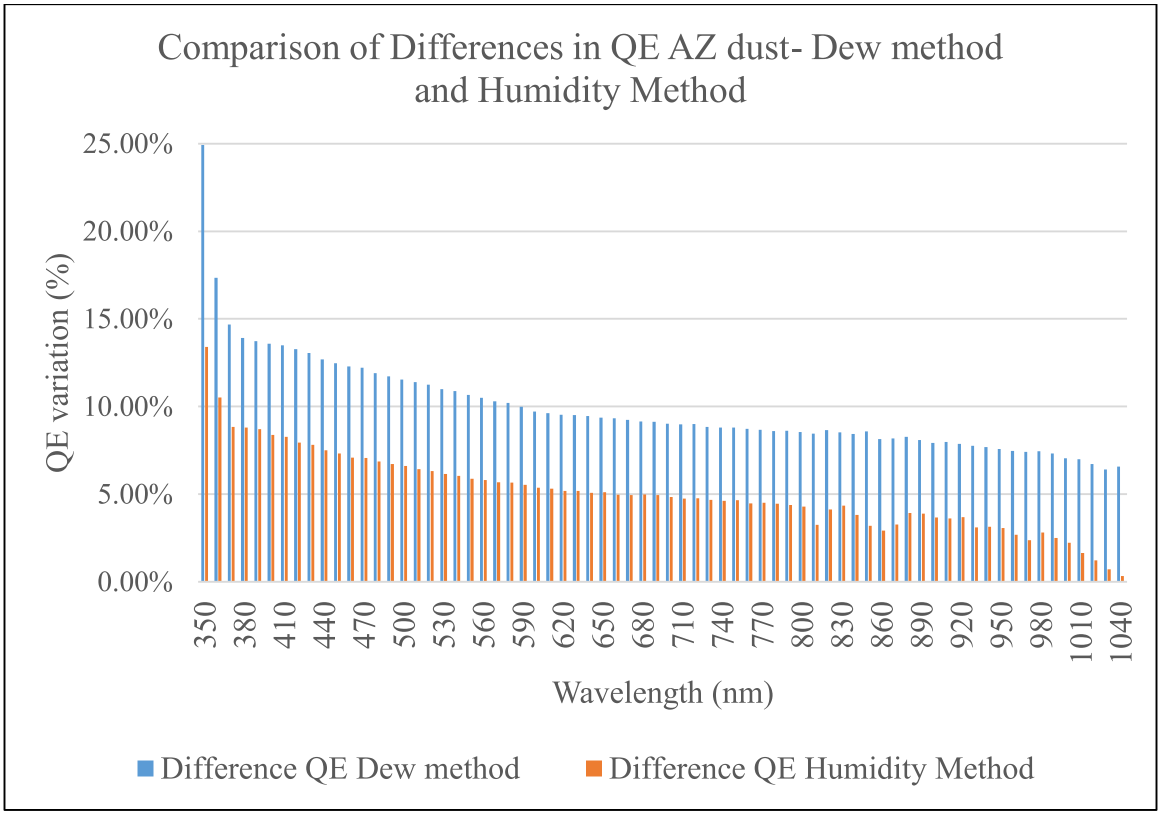


Figure 31: Sample Soiled Comparing AZ Dust For 2 Cycles By The Humidity And Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 g/m2 soil deposition per cycle

As seen in the Figure 31 above, we find that the humidity method shows lesser losses than the dew method. Again, this can be attributed to the higher moisture condensation for the dew method as compared to the humidity method for the same amount of soiling time of 1 minute after blowing the N_2 compressed gas.

4.4 Glass Coupon Transmittance

The following chart shows the results of the transmittance measurements taken for the glass samples at NREL. The method of soil deposition is the Dew method.

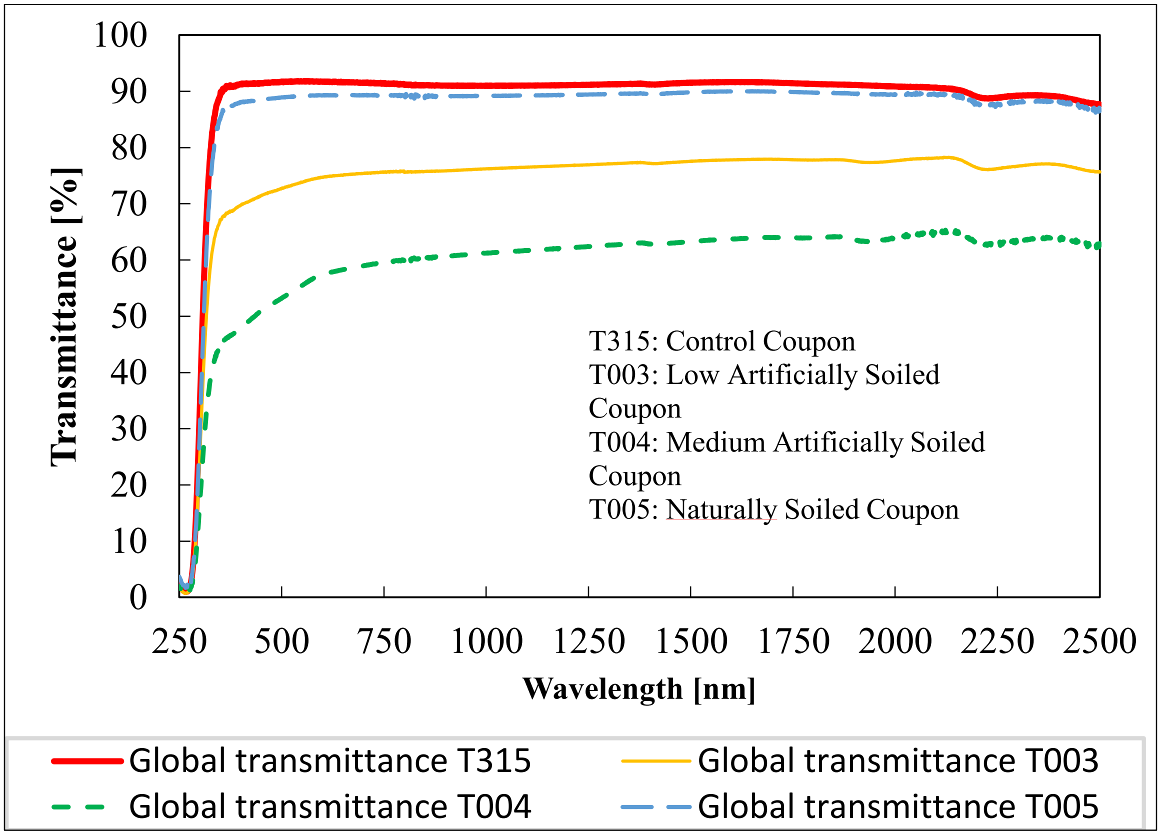


Figure 32: Transmittance Values For Sample Soiled Comparing Collected Soil For 5, 10 Cycles By Dew Method Using Approximately 2 Grams Of Sample Soil In Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 g/m2 soil deposition per cycle

The loss in the transmittance values as reported by NREL is in line with what is expected for irradiance losses due to soiling intensity. If we look at the figure, we see that the curve for T005 shows the soiling transmittance through a sample placed outdoors for three weeks, from February 11, 2016- March 2, 2016. As the other curves correspond to the transmittance through the samples, this could be used as an estimate of the artificially soiled sample as a measure of the outdoor soiling intensity. For example, the curve for the low artificially soiled sample (T003- 5 cycle Mesa soil deposition) could correspond to a real world outdoor soiling of around 15 weeks. Similarly the curve corresponding to the medium artificially soiled sample (T004- 10 cycle Mesa soil deposition) could correspond to a real world outdoor soiling of around 30 weeks.

Below we see an example of a sample glass coupon before and after soiling by the dew method. This glass coupon was then sent to NREL for transmittance testing and soil composition studies.

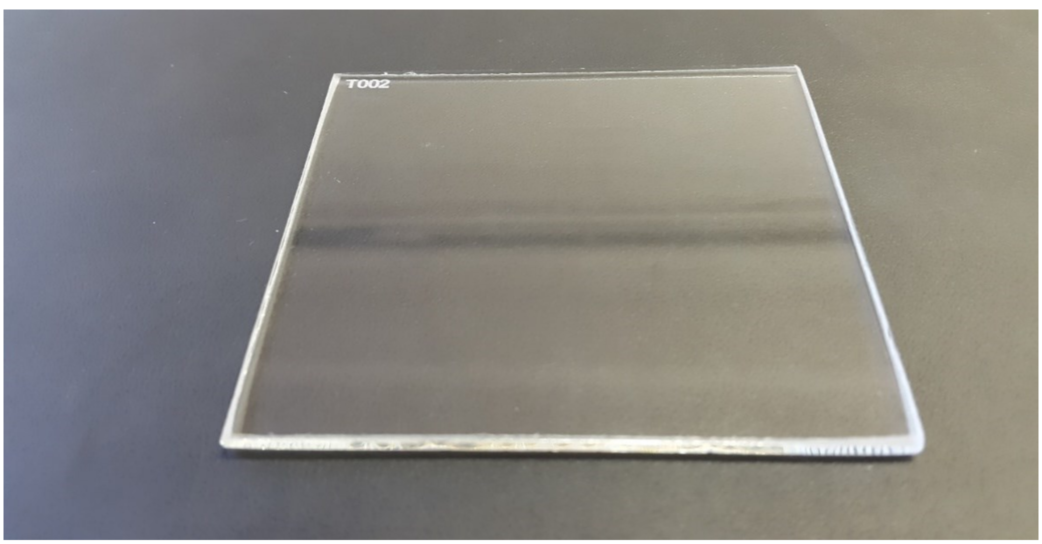


Figure 33: A Clean Glass Sample Coupon

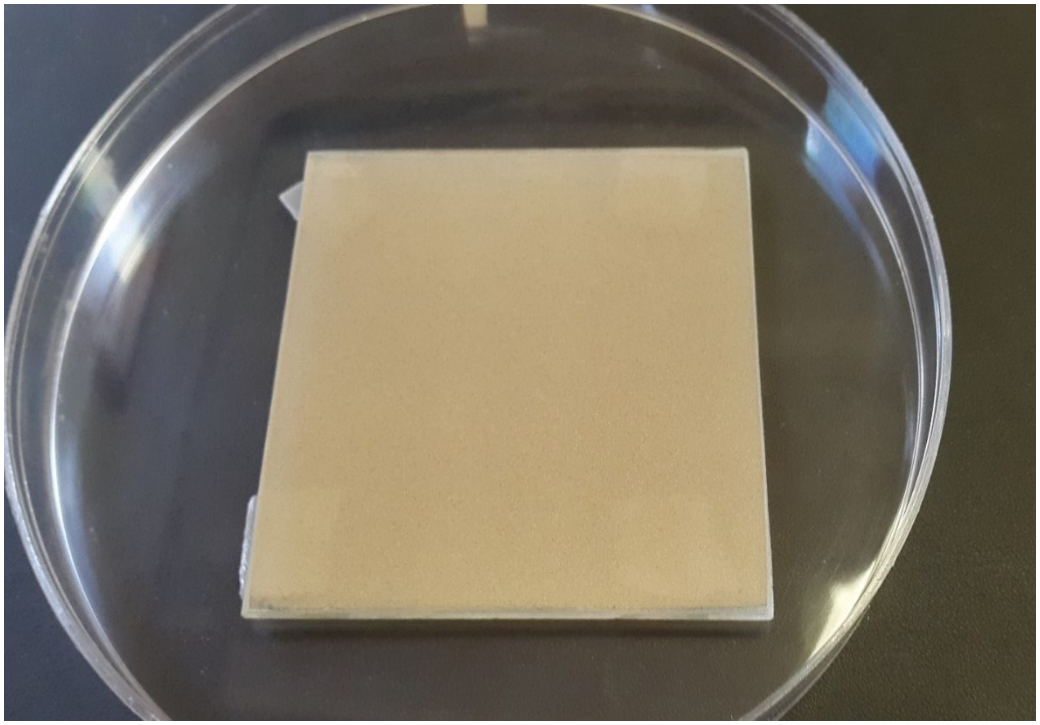


Figure 34: A 10 Cycle Soiled Glass Sample By The Dew Method Using Approx. 2 Grams Of Sample Soil In The Soil Dispersion Chamber And 1 Minute Of Settling Time And A Soil Density of $1.46 g/m^2$

As seen in the sample Figure 34, the soiled sample shows a very uniform layer of Collected Mesa soil on the glass sample. This soil layer is the result of the soil deposition of 10 cycles of Collected Mesa, AZ soil by using the dew method of soil deposition. This10 cycle deposition of the collected soil gives a soil density approximating to around $15 g/m^2$. This soiled sample was then sent for SEM analysis to NREL which shows a few interesting results which are discussed in the following segments.

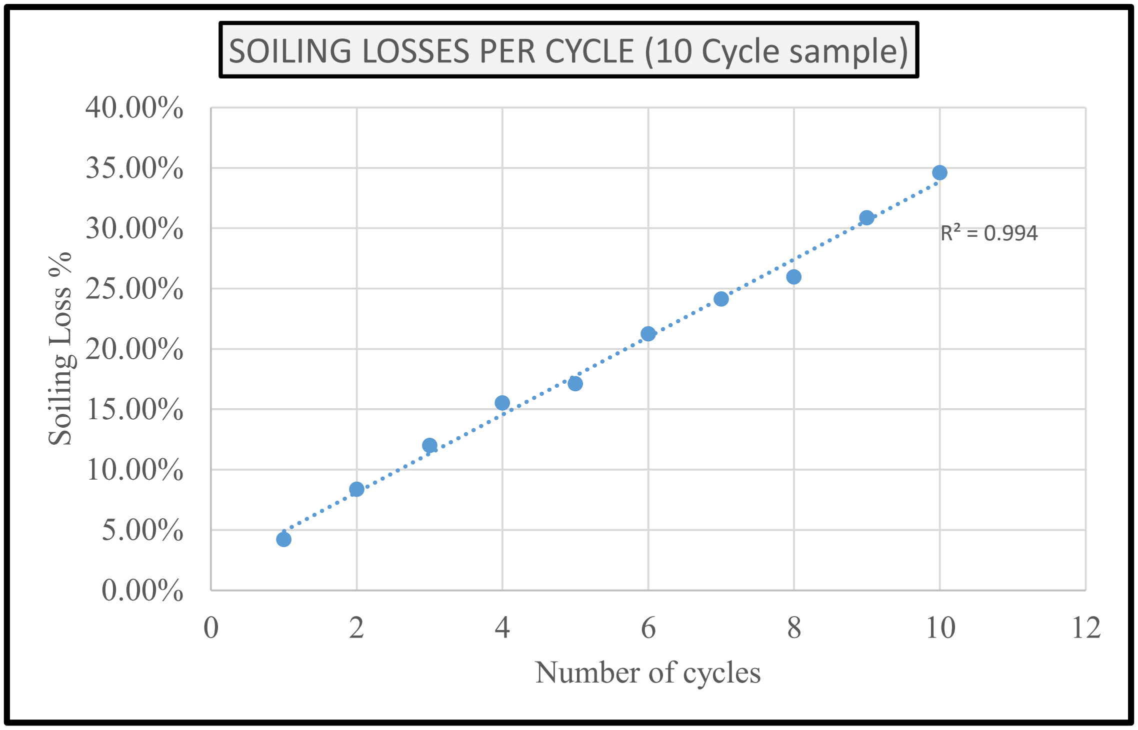


Figure 35: 10 Cycle Collected Soil Deposited Glass Sample Showing Transmittance Loss In The Linear Trend For Sample Soiled Using Approx. 2 Grams Of Soil In The Soil Dispersing Chamber And Approx. 1 Minute Of Settling Time For Soil Density Of Around 1.47g/m^2

The glass coupons sent to NREL were soiled for multiple cycles to get higher soil deposition to simulate high soiling conditions on a module.

The graph above shows that the transmittance losses observed for the 10 cycle deposited sample with each deposited soiling cycle follows a linear pattern. This linear trend can be an indication of the soil uniform deposition on the glass sample. The soiling loss was measured as a factor of the voltage loss with respect to the number of cycles through which the glass sample underwent soiling. The linear trend line is seen to be a good fit for the graph with a R^2 value of 0.994. This soiling loss is obtained by adjusting the measured value of the reference cell to the measured value of the reference cell before the soiling was done.

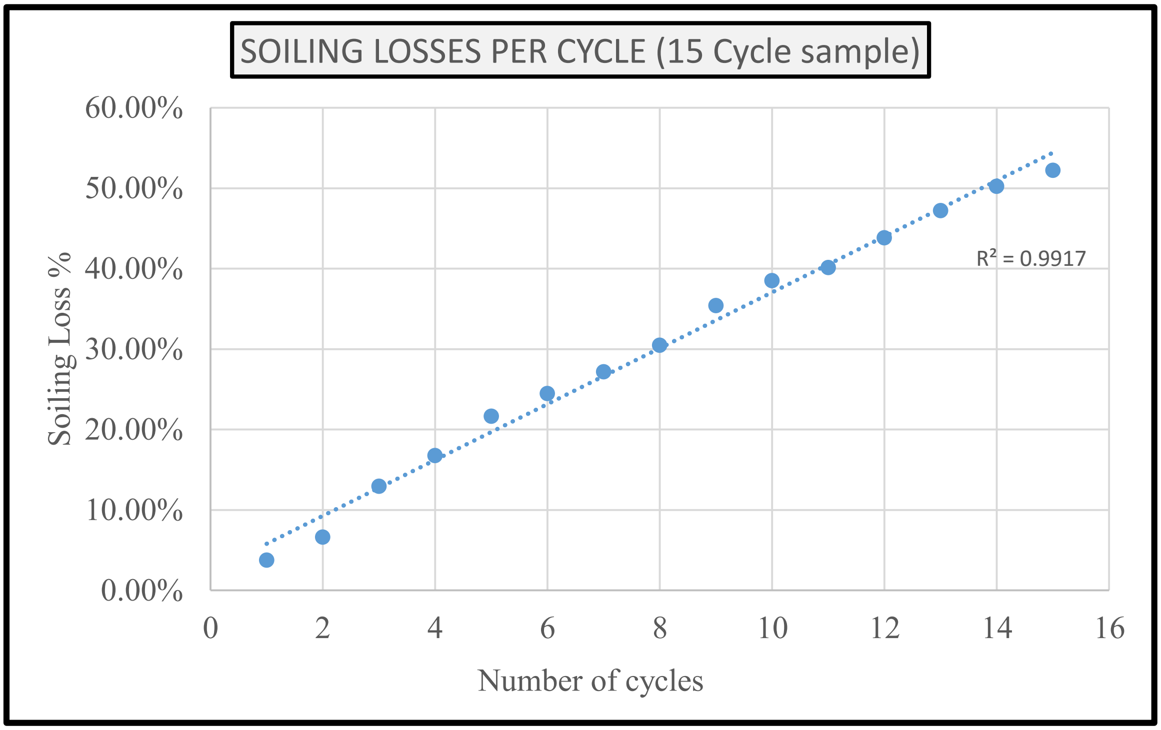


Figure 36: 15 Cycle Collected Soil Deposited Glass Sample Showing Transmittance Loss In The Linear Trend For 2 Grams Of Soil In The Soil Dispersing Chamber And Settling Time Of Around 1 Minute And Soil Density Of Around 1.49g/m^2

The Figure 36 shows the transmittance loss through a sample which has been soiled with 15 cycles of Mesa, Arizona collected soil. As seen in the figure, the losses show a linear trend with each soiling deposited cycle. This linearity could be an indication of the soil deposition uniformity for each cycle. This linear trend has a R^2 value of 0.9917 which indicates the very good fit for the linear trend. As the glass sample increases in soiling cycles, we see that the soil deposition uniformity increases.

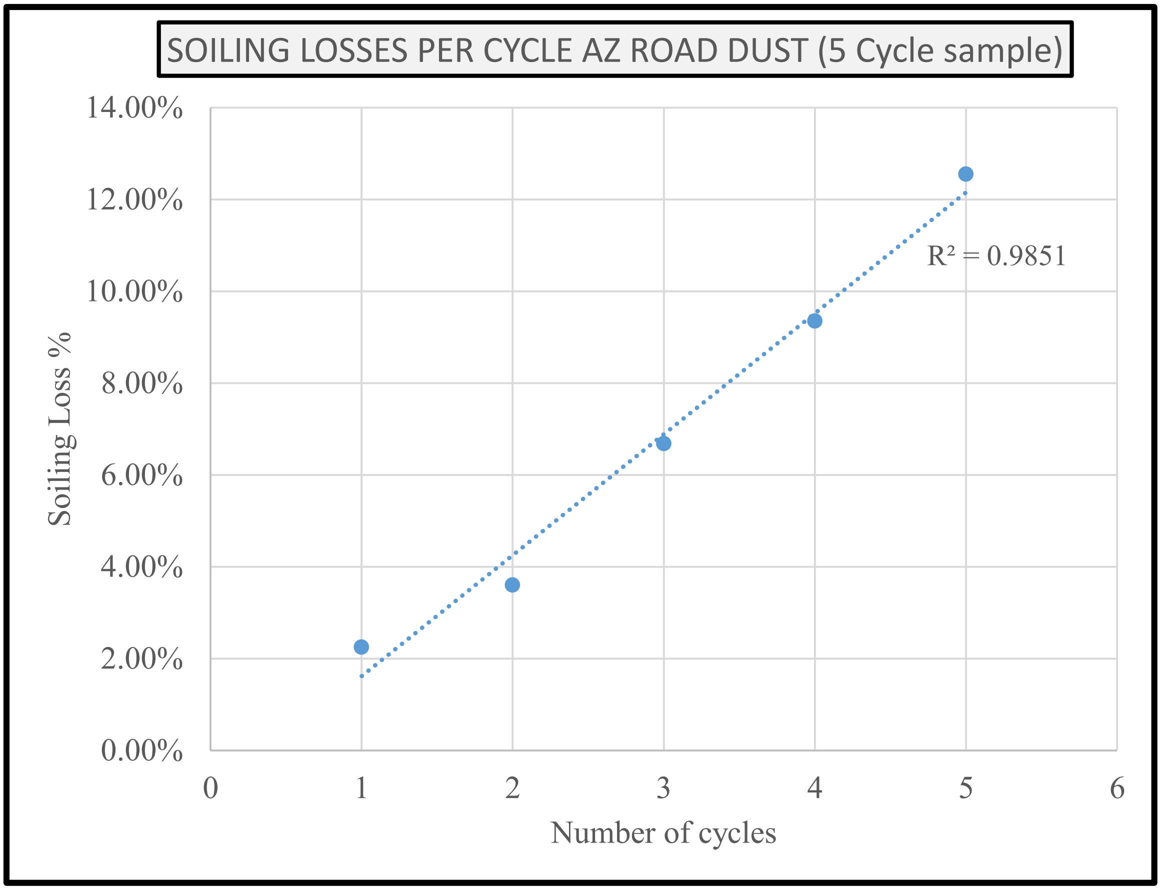


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Figure 37: Transmittance Losses Seen due to the 5 Cycle Deposition of AZ Soil on a Glass Coupon for 2 grams of soil in the soil dispersing chamber and settling time of around 1 minute and soil density of around 1.49g/m^2

This Figure 37 shows the transmittance loss due to the AZ dust soil deposition of multiple cycles on the glass sample. This particular graph figure is that after the glass sample was deposited with 5 cycles of AZ dust. As seen, the soiling losses per cycle show a linear trend with a R^2 value of 0.9851. This indicates that the soiling losses measured as a factor of voltage losses after every soiling cycle show a very similar increase in losses, thus pointing towards the uniformity of the soil deposition. Thus, we see that different types of soil can be used to deposit on the samples uniformly, provided the number of soiling cycles is high enough.

4.5 Soil Composition

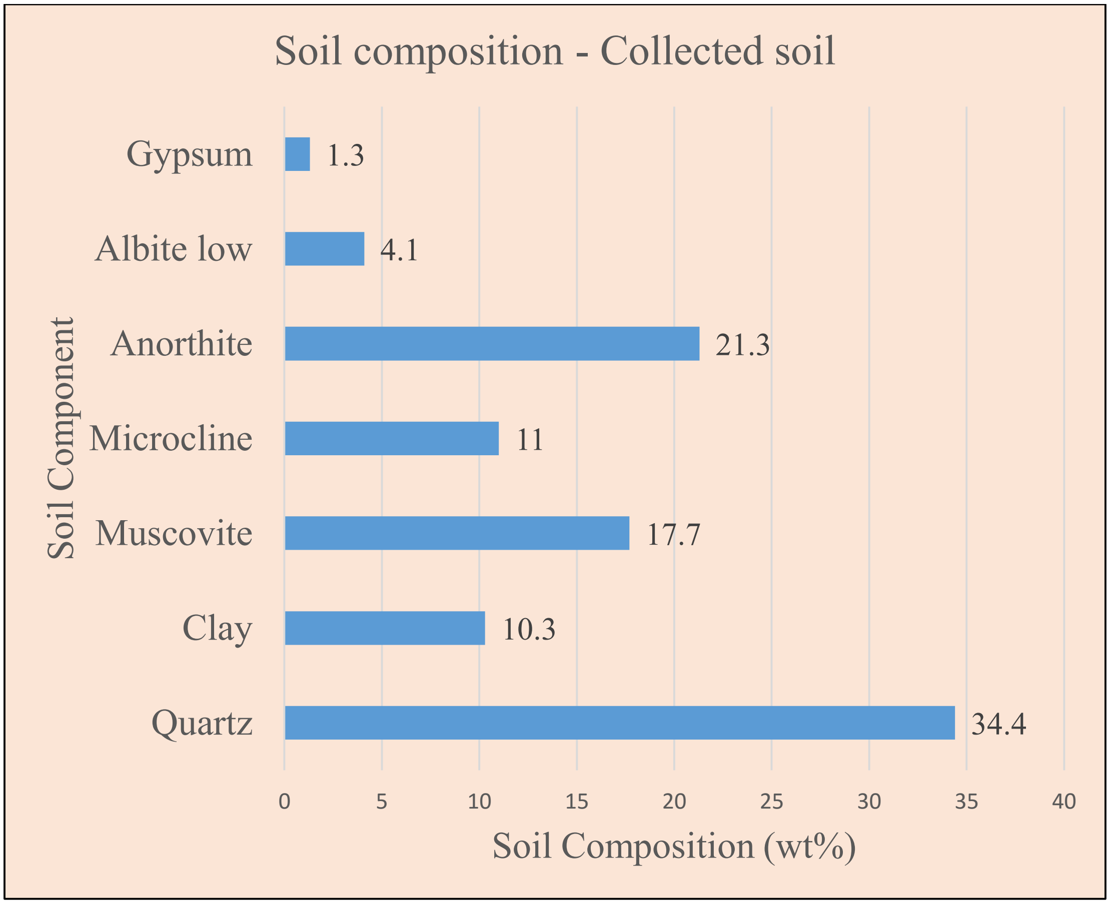

Figure 38: The Soil Composition Of The Collected Soil From Mesa AZ For 5 Cycle Using Approx. 2 Grams Of Soil In The Soil Dispersing Chamber And Settling Time Of Around 1 Minute And Soil Density Of Around 1.49g/m2

In the Figure 38 we find that the soil collected from the modules in the solar field at ASU PRL has a high percentage of quartz in its composition. The other composites also show a certain percentage of anorthite and muscovite. Compared to the studies made by john et al, where he found that most of the soil samples collected from parts of India contained quartz as its most important constituent, in the soil collected in Mesa, Arizona, the composition is showing a similar trend. This indicates that the climate and the soil type will affect the soiling of the modules. This also indicates that the soil adhesion on the module is highly dependent on the soil constituents.

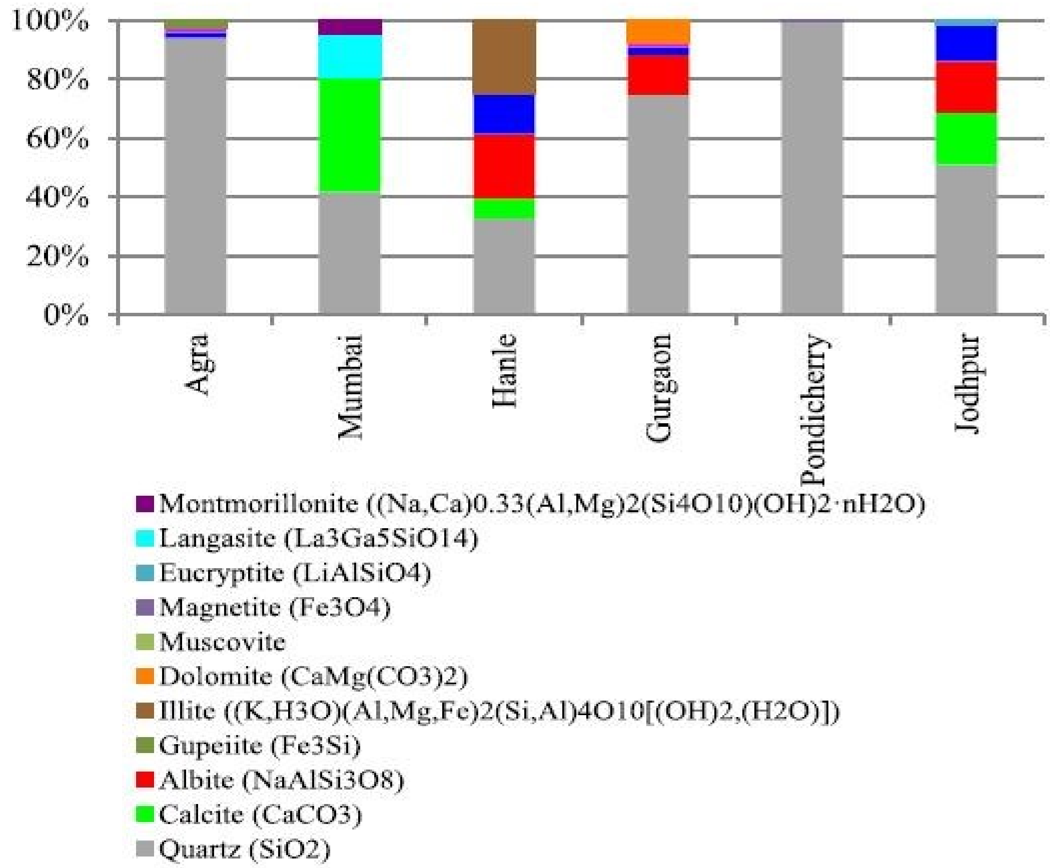

Figure 39: The Soil Composition for Different Soil Samples Collected Across India *[6]*

As seen from the Figure 39 above, the soil composition for soil samples found in India, the major component is Quartz, which is similar to that found in the soil collected in Mesa, Arizona. However, as the comparative study suggests, the soil composition changes from region to region, which will have an effect on the soiling density and the characterization of the soil collected.

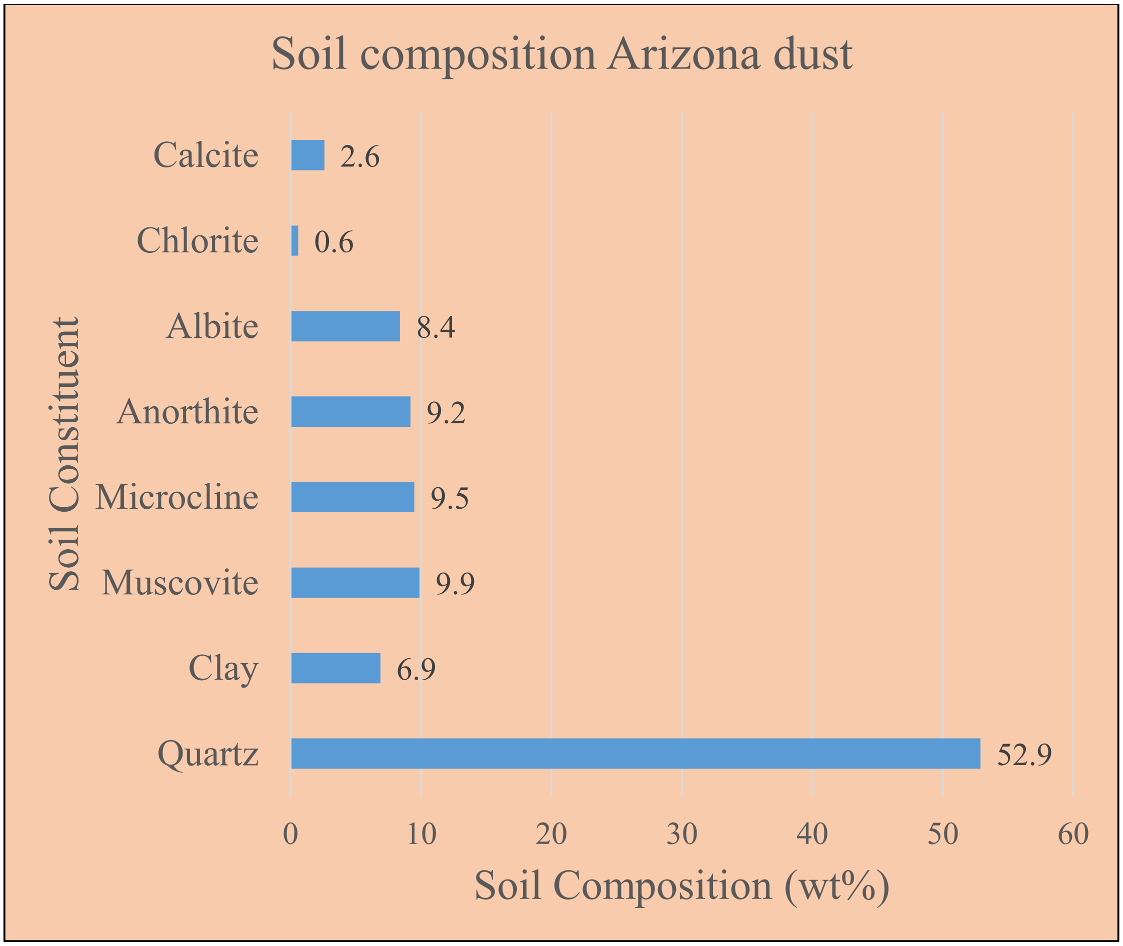

Figure 40: The Soil Composition Of The Standard Soil AZ Dust For 5 Cycle Using Approx. 2 Grams Of Soil In The Soil Dispersing Chamber And Settling Time Of Around 1 Minute And Soil Density Of Around 1.49g/m2

In the Figure 40 we find that the soil collected from the modules in the solar field at ASU PRL has a high percentage of quartz in its composition. The other composites also show a certain percentage of anorthite and muscovite, but these values are very close to each other.

PARTICLE SIZE DISTRIBUTION AND SEDIMENT TYPES

	% of total Sample		
D (μm)	Jodhpur	Mumbai	Sediment Type
0–4	9.26	22.31	Clay
4–8	5.09	15.74	Very Fine Silt
8–16	15.32	28.61	Fine Silt
16–31	31.83	26.18	Medium Silt
31–63	27.78	7.15	Coarse Silt
63–125	10.71	0.00	Very Fine Grained
125–250	0.00	0.00	Fine Grained
250–500	0.00	0.00	Medium Grained
500–1000	0.00	0.00	Coarse Grained

Figure 41: The Particle Size Distribution for the Soil Collected from different Regions of India *[6]*

As seen from the Figure 41 above, the particle size distribution in India shows that particle size of around 8-30 µm are the most prominent. This is obviously different from the soil composition found in Mesa, Arizona. Having a soil composition with higher soil particle size would mean that the number of cycles required for uniform soil deposition is lower. As the area covered by the coarser soil particles will be higher, hence the logic follows that the uniform soiling intensity can be achieved by depositing that coarse soil in lesser number of soiling cycles.

5.0 CONCLUSION

The soil layers deposited on glass coupons and one-cell PV laminates have been characterized and presented in this thesis. The soil layers were deposited using gravity/dry, dew and humidity methods. This thesis focuses on the characterizations of the soil layers obtained in several soiling cycles using various techniques including current-voltage (I-V), quantum efficiency (QE), transmittance, optical profilometry and compositional analysis.

Soil Deposition Methods: The dry method of soil deposition was seen to have non-uniform soil deposition which was attributed to the big mesh size and the inconsistent vibrational system used and as such, further soil characterization tests were not performed on the samples from the 'dry' method. The 'dew' method of soil deposition was found to give uniform soil deposition on the PV-coupons and the glass coupons. The uniformity of the dew method could be verified by the short circuit current (I_{sc}) characterizations which showed a constant difference in the I_{sc} values measured for the clean and the soiled samples. The surface imaging results showed that the particle count increased in a linear pattern with increase in the number of cycles. As expected, the number of particles seen for 2 cycle deposition, 5 cycle deposition and 7 cycle deposition is in an increasing trend of 760, 1350 and 1780 respectively, indicating that the uniformity of soil deposition increase as the number of soiling cycles increases. Also, it has also been seen that the soil used for the soil deposition will affect the soil uniformity, as it was seen that the soil collected from modules in Mesa, AZ will have lesser soil deposition density than the standard testing AZ dust for the same number of cycles. The 'humidity' method of soil deposition also showed promising results and had uniform soil deposition for the coupon sample. The I_{sc} characterizations showed a constant difference in the values for the clean coupon and subsequent soiled sample values indicating a uniform soil deposition. One important thing to note was as such, it could be seen that for all things being the same for the 'humid' and 'dew' methods, the values of the I_{sc} measurements indicated towards slightly less soiling intensity for the 'humid' method. This was verified by the surface imaging studies which showed lesser particle count for the same number of soil cycles for the 'humid' method as compared to the 'dew' method. This shows that the water condensation rate for the 'dew' cycle is higher than the dust plus humid air deposition on the sample for the 'humid' method.

Current-voltage: The I-V characterization was carried out to determine the uniformity of deposited soil layer, repeatability of soil deposition cycles, and the impact of soil layer thickness and properties on current and other performance parameters of PV devices. The dew and humidity methods yielded highly uniform soil layers as compared to the gravity method. The I-V measurements also indicated that the repeatability level of soil deposition cycles was very high for both dew and humidity methods. For identical soil deposition cycles, the soil deposition level was determined to be high for the reference AZ dust as compared to the surface-collected soil.

Quantum Efficiency: The quantum efficiency measurements showed a slight wavelength dependent QE loss indicating that the soil layer is not a perfect neutral density filter. The QE measurements also showed that the deposition rate is higher for the dew method as compared to the humidity method indicating that the humidified soil particles settle at a lower rate.

Transmittance: As expected, both global and direct transmittance studies indicated that the transmittance loss is proportional to the thickness of soiling layer. As in QE study, a slight wavelength dependent transmittance loss was observed indicating that the soil layer is not a perfect neutral density filter. The cut off wavelength for the QE response was determined to be about 400 nm whereas it is about 340 nm for the transmittance response. The difference in these cut off wavelengths is caused by the difference in properties of the glass pieces used for the transmittance and QE measurements. The glass piece used in the PV cell coupon contained cerium oxide whereas the glass piece used for the transmittance measurement did not contain cerium oxide.

Optical Profilometry: The number of particles in the AZ dust for the same number of cycles (five cycles) is higher (1670 particles) than in the surface-collected soil (1350 particles). Also, the particle sizes seem to be larger for the AZ dust sample as compared to the surface-collected soil sample. This is consistent with the conclusions made from the I-V and QE measurements which indicate a higher current and QE losses for the AZ dust as compared to the surface-collected soil due to difference in soil densities.

Soil Composition: About 63% of the surface-collected soil sample in Mesa, Arizona contains anorthites (plagioclases), muscovites and quartz. These compositional properties do not seem to make any significant differences except in the low wavelength regions of QE and transmittance curves. However, these properties are expected to make significant differences in the adhesion strength of these particles on the glass surface. Comparing the results of the soil constituent's analysis of Mesa, Arizona with the results of a similar soil analysis in India indicates that the major component of the soil in Mesa is quartz, which is the same as the soil collected from some of the parts of India which indicated quartz as the major constituent.

Recommendation: This study recommends to perform these and other characterizations including adhesion tests on the soil layers deposited using the surface-collected samples from various regions of the United States, and the world. This soiling study has a number of scopes for improvement. The next step in this study would be to build an artificial soiling station for the module level with similar testing conditions as that of dew and humidity methods. It is also to be noted that while non-uniform results were obtained for the gravity/dry method, improvements in the mesh size and soil deposition component, along with an automated system to move the soil dispenser could possibly increase the chances of achieving uniform soil deposition.

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APPENDIX I

SOIL CHARACTERIZATION DATA

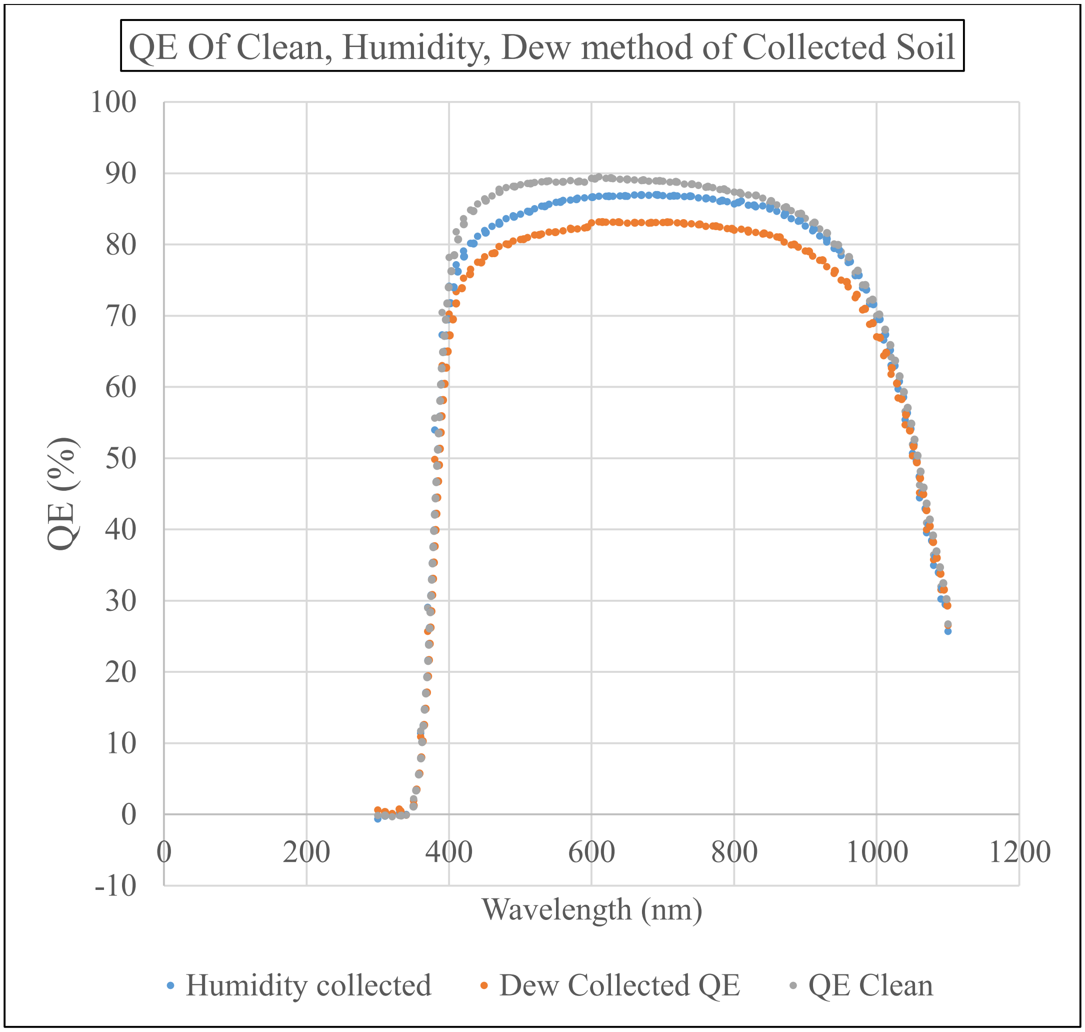

Figure 42: The Comparison Of The QE For The Dew And Humidity Method Using Collected Soil From Mesa, Arizona Soil For 2 Cycles By The Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 G/M2 Soil Deposition Per Cycle

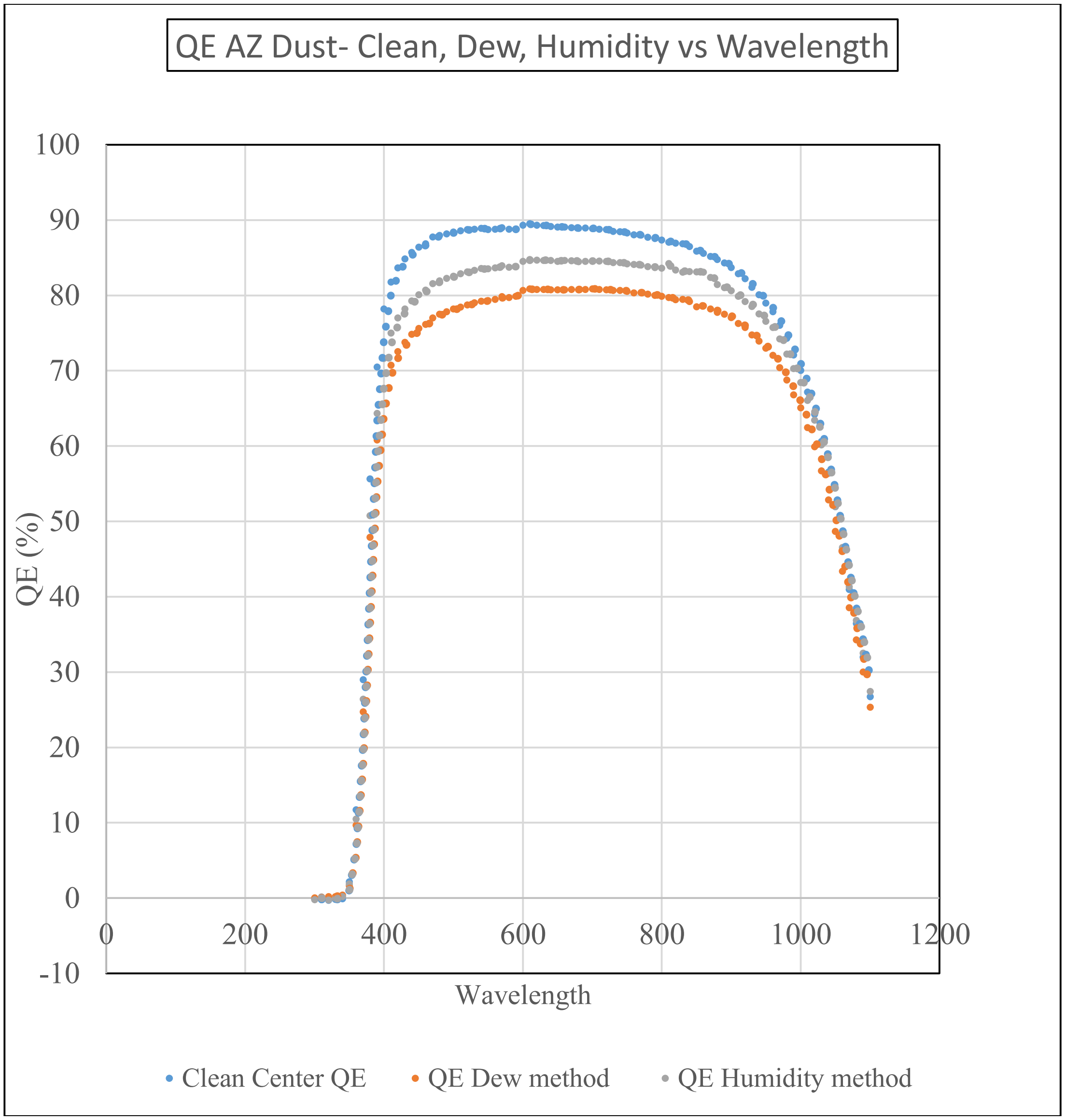

Figure 43: The Comparison Of The QE For The Dew And Humidity Method Using AZ Dust From Mesa, Arizona Soil For 2 Cycles By The Dew Method Using Approximately 2 Grams Of Sample Soil In The Soil Dispersion Chamber And Approximately 1 Minute Settling Time And Approx. 1.45 G/M2 Soil Deposition Per Cycle

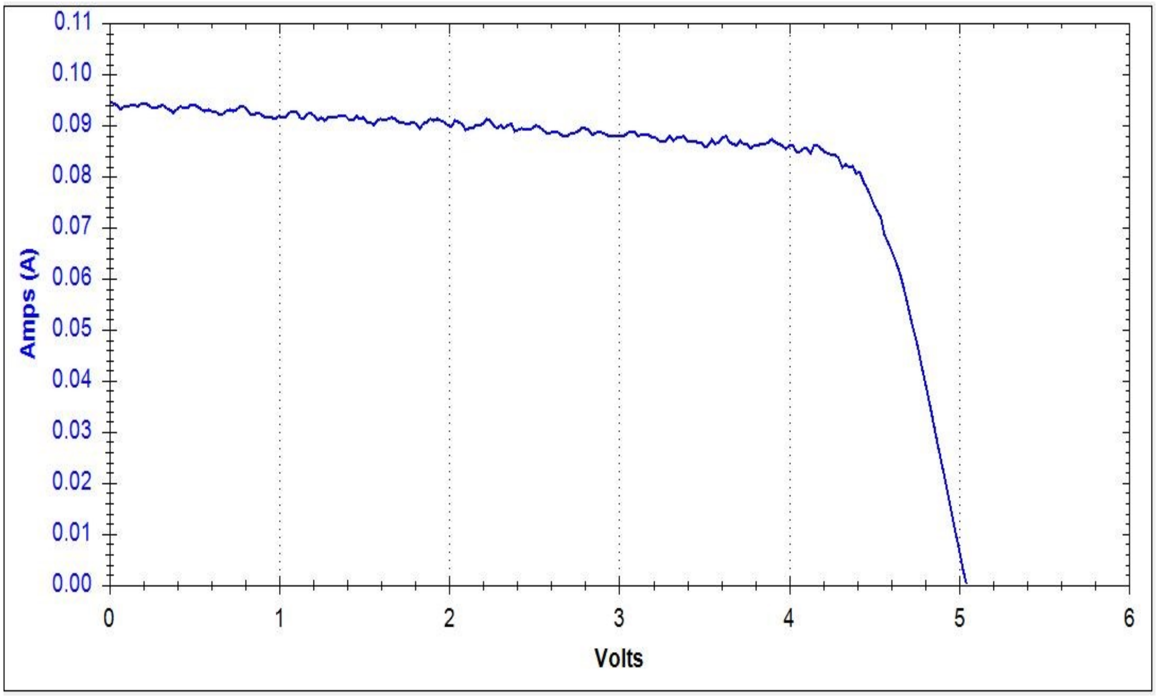

Figure 44: Current-Voltage Curve for Clean Mini-Module

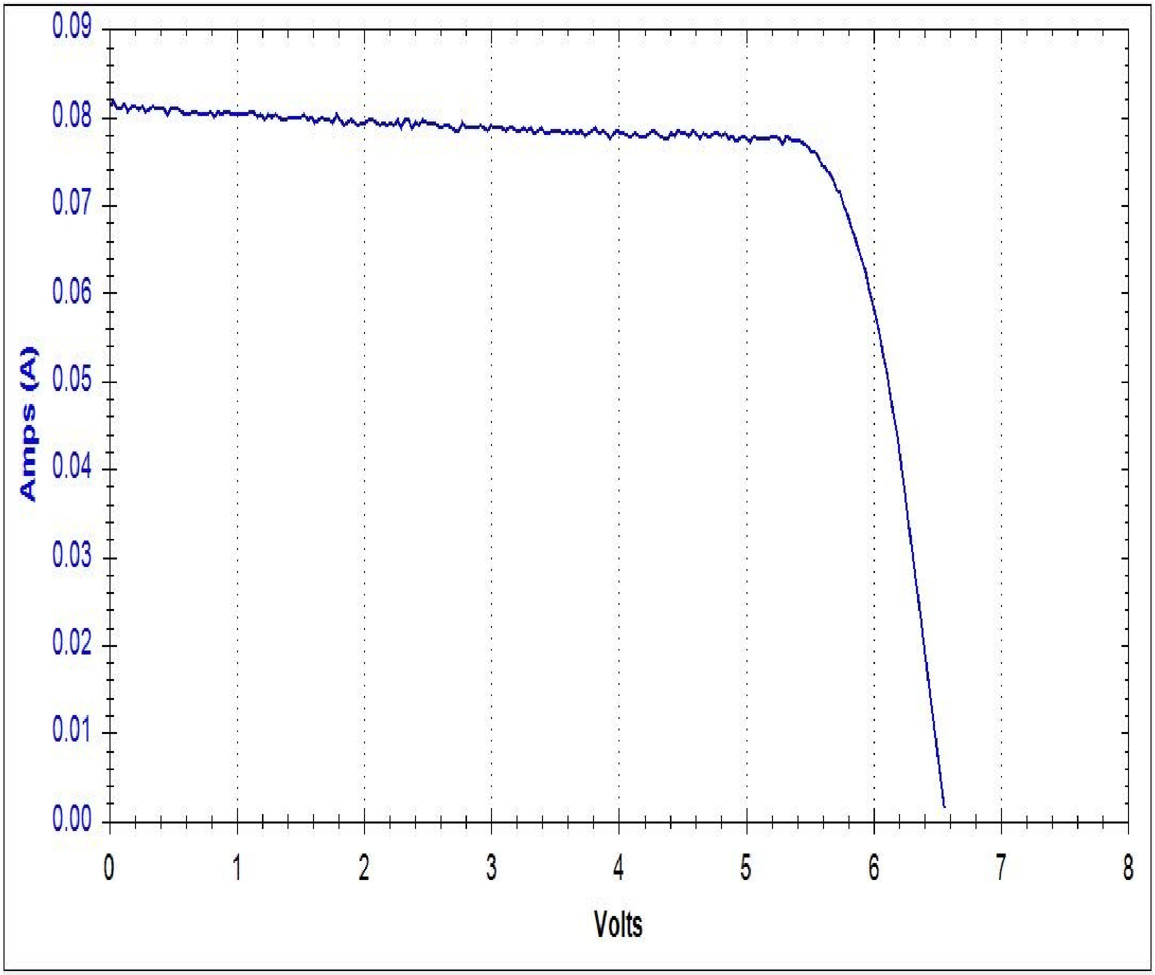

Figure 45: Current-Voltage Curve For Soiled Mini Module With Collected Soil From Mesa, Arizona With 2 Grams Of Soil With 1 Minute Of Settling Time And Soil Density Of Around 1.47g/m^2

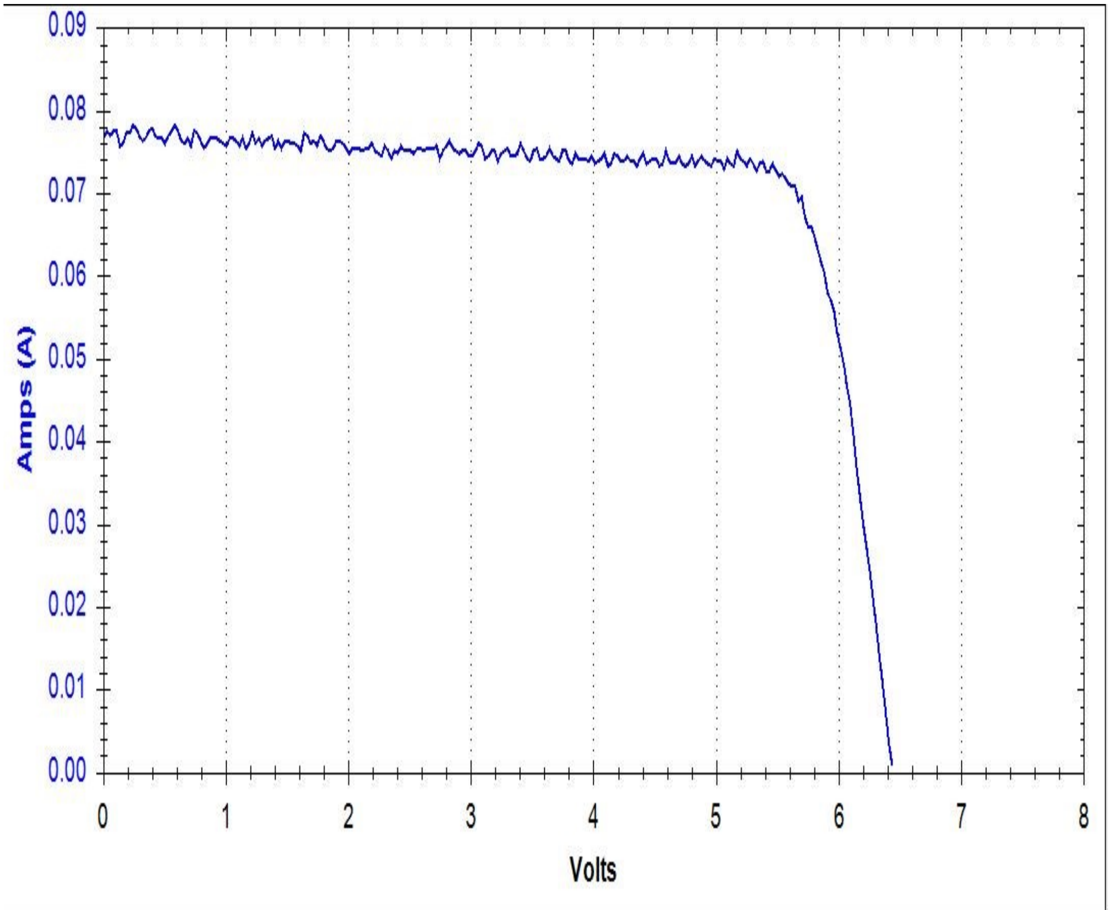

Figure 46: Current-Voltage For Soiled Mini-Module With Arizona Dust Using 2 Grams Of Sample Soil And 1 Minute Of Settling Time And Soil Density Of Around 1.48g/m^2

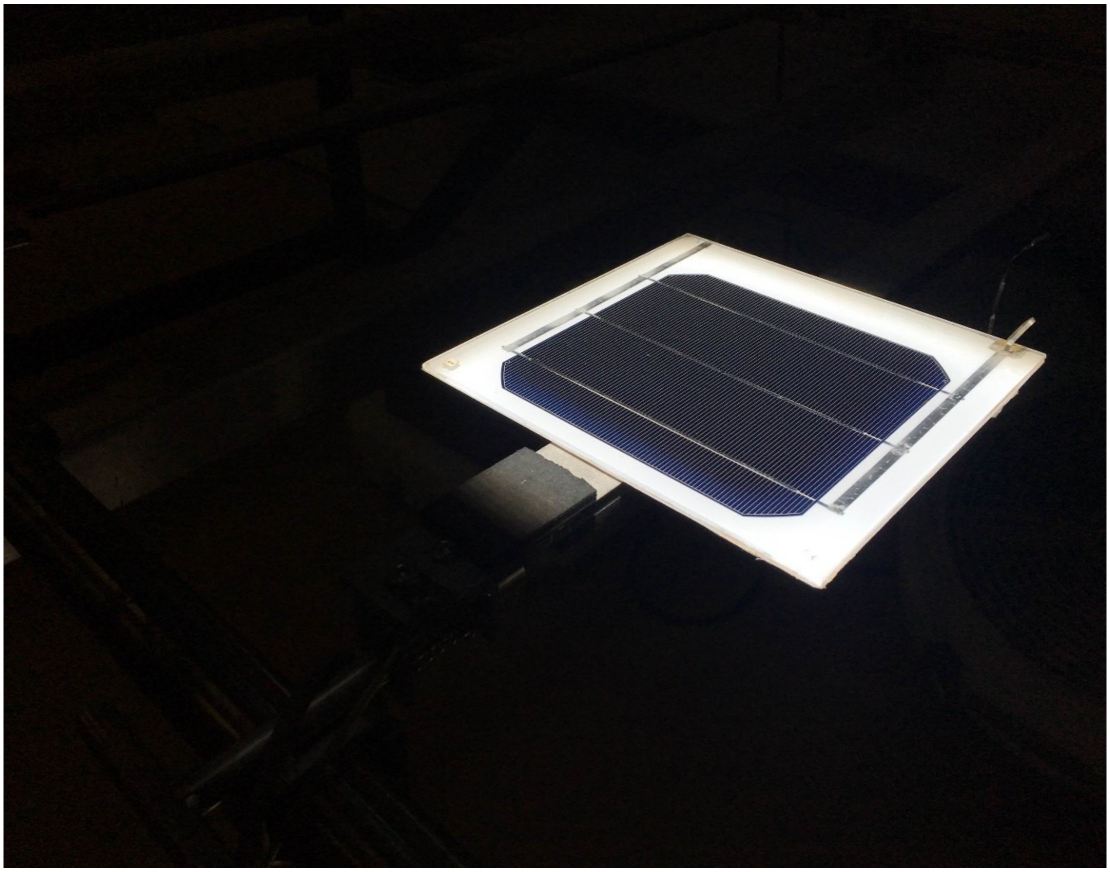

Figure 47: Coupon Placed Under the Indoor Solar Simulator for Measuring Isc

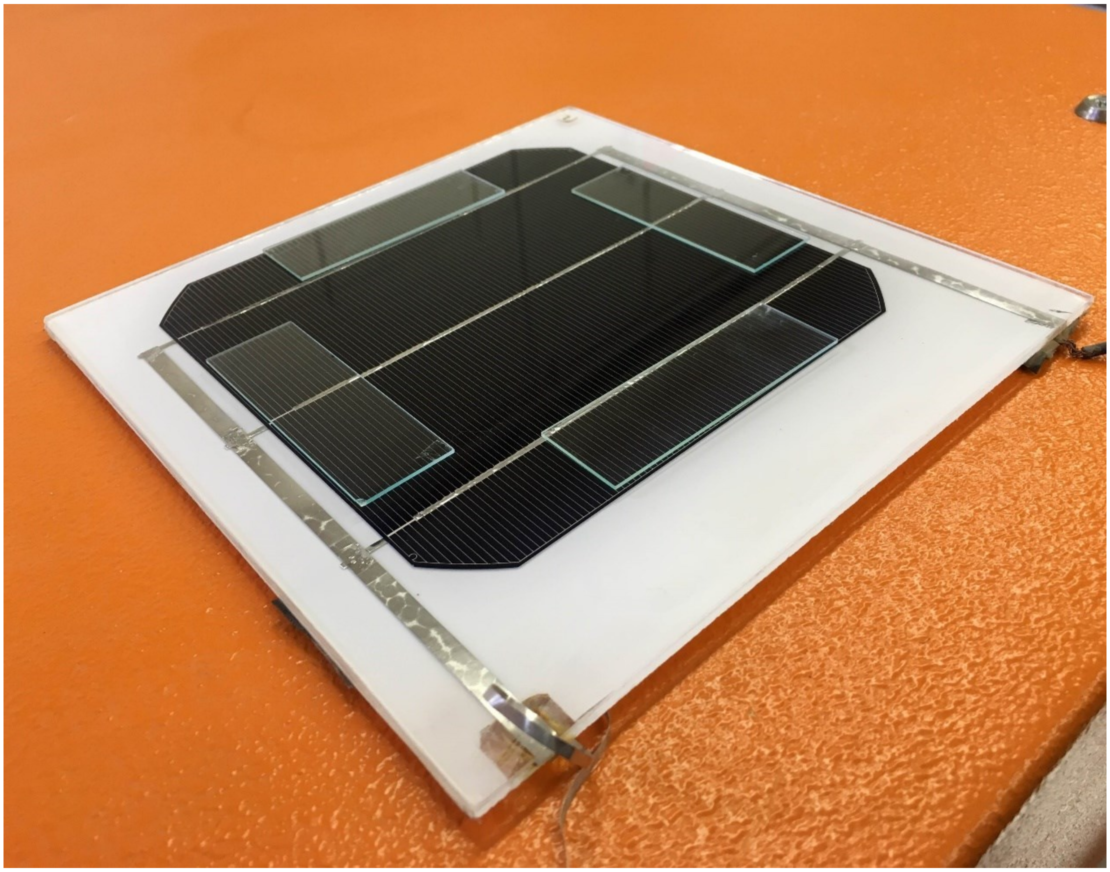

Figure 48: Position of the Slides to Measure their Weight and Verify the Uniformity of the Soil Deposition

Figure 49: Coarse non uniform soil deposition after 5 cycles of using Dry method