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Graphene Coated Geotextiles: A Proof of Concept

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Abstract

The specific objective of this project was to examine the tensoresistivity response of graphene-coated geotextiles through laboratory tests. The geotextile samples in this project are tested in tensile and twisting modes simulating their conditions in the field. Over the past few decades, geosynthetics have revolutionized many aspects of civil engineering practice. However, over time geosynthetics can lose elasticity and become less effective. Therefore, sensors are often used to detect deterioration in the material. Using graphene-coated geotextiles allows for a charge to be through the material, which allows for the detection of changes in the extension of the material by noting changes in the electrical resistance. This eliminates the need for sensors and increases the accuracy of the data collected on geotextile deterioration at reduced cost, which has not done before. Both the tensoresistivity and mechanical performance of graphene-coated geotextile specimens were examined. In the first series of tests, samples of the material were mounted on a universal testing machine, and two electrodes were attached to the specimen. The specimens were then subjected to tensile loads. In the second series of tests, the specimens were subjected to torsion. One full cycle of twisting angle up to 90 degrees and back was applied to each specimen at different pretension loads. The change in the resistivity as a function of the twisting angle and tension was recorded and plotted. This preliminary data indicates that all samples show consistent and practically linear tensoresistivity responses over the lower range of strains ($e \leq 15\%$) that are of practical interest.

Keywords: Geotextile, Strain, Resistance

1. Introduction

Geotextiles are commonly used to reinforce soil in highway embankments, dams, and other structures, which prevents soil erosion, foundation destabilization, and inefficient construction practices.[8] Geotextiles are also very important in designing drainage.[3] Monitoring the stability and "health" of these important materials increases the safety of structures and streamlines construction timelines, which saves money. One example of this is contractors must wait for soil to settle in construction sites before they can safely continue their project, which is expensive and time consuming. Performance monitoring makes information about soil settling more available which allows construction to operate efficiently and safely. The health of a geotextile refers to the amount of strain and deformation the material has undergone. Depending on the material strength, this will indicate how close the geotextile is to failure. If the material is conductive, its electrical resistance can indicate how much deformation the material has undergone. When these two variables are reliably related, they can be standardized for field applications. To make the geotextiles have a conductive element, a graphene coating was applied on one side of the geotextiles used in the following experiments. A carbon-based material is used instead of a metal-based material because metal oxidizes.[5] Previous experiments analyzed the relationship between adding carbon-filled polymeric materials and their tensoresistive and mechanical properties. In one study, the percolation threshold for carbon black coatings on geotextiles was examined, and it was

shown that this concentration varies with the type of carbon fiber used, so consistency in the coating is important for consistency in the results.[1] Another study examined the percolation threshold with an increase in the carbon concentration in geogrids and geosynthetic coatings which resulted in a sudden jump in the measured electrical conductivity due to an increase in pathways from the increased concentration.[4] Additionally, there was a study that analyzed the effect of blending carbon black into a geotextile, but it was found that the blending of carbon black into the material at a sufficient concentration for conductivity weakened the material.[5] Thus, the methods for developing the coating for the geotextiles used in the following experiments have already been developed. Several current paths exist between any two points on this graphene coating. As a tensile load is applied, the connections between the carbon fibers of graphene are broken, which manifests as increased resistance. This phenomenon was called tensoresistivity.[7] The sensitivity of this property is determined by the percolation threshold, which is related to the amount of carbon in the coating. The goal is to have an optimal amount of graphene that provides enough current paths to have a resistance even when the material deforms, so data are always available, but not so many that breaking some paths does not noticeably affect the resistance, so that when the material deforms it would be noticeable by reading the resistance measurements. Other studied looked at in-isolation versus in-soil tests and found soil showed higher conductivities at 10^{-2} S/m than the specimens did at 10^{-5} S/m. It is also important to note that in-isolation tests cause the specimens to have greater strain sensitivities at slower strain rates.[2] This indicates the data observed in the following experiments are an exaggerated representation of the resistance response of the geosynthetic materials. Similar research has also been done with geogrids.[6] Thus far, this is proof-of-concept research, intended to identify that the tensoresistive properties exist and determine their reliability and sensitivity for a given material.

2. Materials

The materials of primary importance in this experiment were the geotextiles themselves. Two different materials, all of which can be viewed in Figures 1 and 2, were used and had different behaviors over the course of the experiments, which included a polyester material and a polypropylene material. Polyester was shown to have high levels of deformation as well as a high sensitivity, meaning it showed large changes in resistance for relatively small deformations. Polyester is additionally weather resistant and not prone to abrasions.[2] Polypropylene showed lower levels of deformation and tended to stay intact under large amounts of stress and then snap suddenly, giving it a lower sensitivity than polyester. Both samples were coated with graphene on one side, which has a negligible effect on the strength of the materials.

To test these geotextiles, a variety of other materials were used. The first was a set of custom electrodes. Because the resistivity of the geotextiles needed to be measured constantly, these electrodes ensured the geotextile always remained part of a closed circuit. These were made of two small pieces of plastic, held together with a small screw on each end. The geotextile was designed to fit in between the two pieces of plastic, and the screws could be tightened or loosened to release or hold the material. In the middle of one of the pieces of plastic, facing inwards, was a 0.4-inch-wide conductive plate, designed to be lined up with the conductive side of the sample. Short, metal rods extended from each side of the electrode, on which alligator clips were clamped. The wires attached to the alligator clips were inserted into a Keithley 2000 multimeter to measure resistance. The material was stretched in a United Universal Testing Machine, which was linked to a computer. Here, data on the force (lbs) and extension (in.) were obtained. Phone cameras were used to record the data from the multimeter, and a timer was used to accurately compare the data from the pictures (resistance) and computer (force and extension).

Figure 1. The setup for the experiment, including the geotextile in a Universal Testing machine with the custom electrodes and wires attached, as well as the Keithley 2000 Multimeter, and the timer.

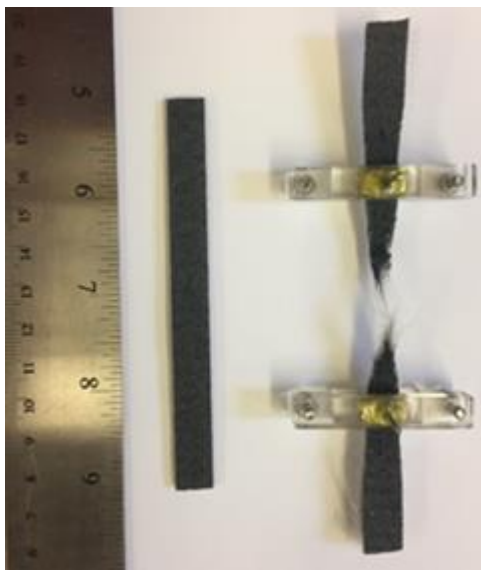

Figure 2. Geotextile specimen before and after it has been stretched to failure, together with custom electrodes

3. Methodology

The methodology was intentionally varied over trials. This was done to see how well the relationship between resistance and deformation would hold up in varying conditions, since conditions naturally vary the field. The following are the standard conditions under which the majority of the experiments were conducted. Six different geotextile samples were used and labeled s17061501, 02, etc. These six samples were cut from three different rolls of material, two samples from each roll, to determine how the packaging affected material behavior. Of the three rolls, the first two were polyester (PET), and the third was polypropylene (PP). Therefore, samples 01-04 were polyester and samples 05-06 were polypropylene.

To begin, all experiments were run using all the samples, but sample size was later reduced to focus on the differences between polyester and polypropylene. This is because packaging issues became less of a priority.

The specimens had measurements of 4”×0.4” and were only cut where the material had not been folded during packing. The specimen was then clamped in the custom-made electrodes, using one or two-inch gauge lengths depending on the trial. These specific gauge lengths were chosen because they are practical and small enough to increase material sensitivity. Once the experiments were set up, data were collected as the specimens were subjected

to various degrees of tensile loading and/or twisting. A strain rate, the rate at which the tensile load was applied, of 10% was used throughout the experiments. This specific strain rate was chosen because it is in compliance with ASTM D4595, close to realistic standards, and practical for preliminary testing.[9] However, 10% is probably much faster than strains in the field. Table 1, found below, is a summary of the different trials covered in this research.

Table 1: Trials covered in research

Name	Description	Why
Testing to Failure	Tensile load was applied until material failed (when the force required to stretch the material decreased)	To establish the relationship between resistivity and tensile loading.
Loading and Unloading	Materials were repeatedly loaded to a set strain and then unloaded until the force on them equaled zero. This process was sometimes done multiple times on the same sample. Sometimes only new samples were used.	To simulate repeated loadings.
Twisting	The material was twisted laterally at different tensile loads and speeds.	To simulate uneven forces on the materials.

4. Experiments

All tests were done to compile data on the samples and to quantify how different types of loading will affect the material.

4.1 Testing to Failure

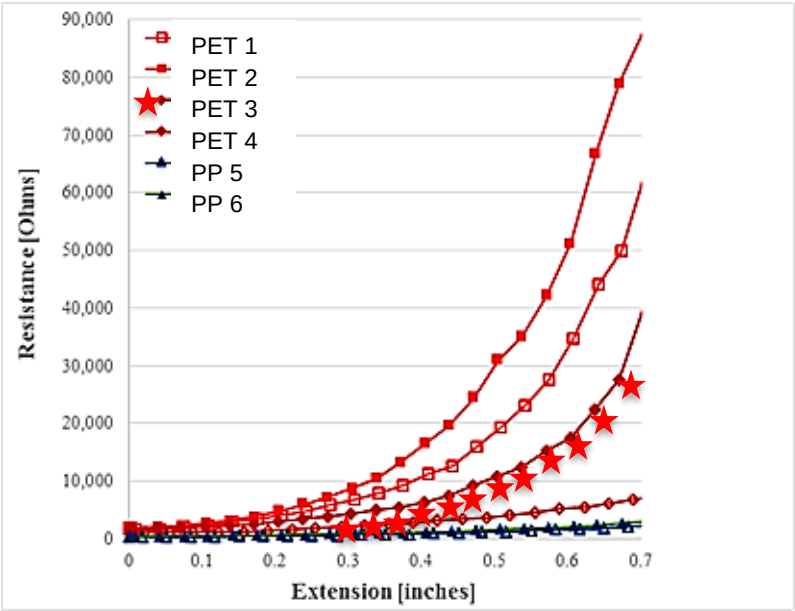

Figure 3. Tensoresistivity responses of graphene-coated PET and PP specimens

For this test, samples were put into the universal testing machine and stretched until failure, or breakage. The resistance of the sample was measured and compiled to show reliability and behavior of geotextiles to later compare to field data. It was concluded that the polyester samples showed the greatest amount of tensoresistivity and greatest sensitivity of coating to resistance changes, and deteriorated as they were stretched. The polypropylene samples showed significantly less tensoresistivity, meaning they needed more extension to show any changes in resistance, and broke more suddenly after showing less deterioration. This is evident in Fig. 3, in which the red and blue/green lines represent polyester and polypropylene samples respectively. The red lines show greater changes in resistance as strain rates increase. This test was conducted to note the behavior of the material when undergoing tensile loads.

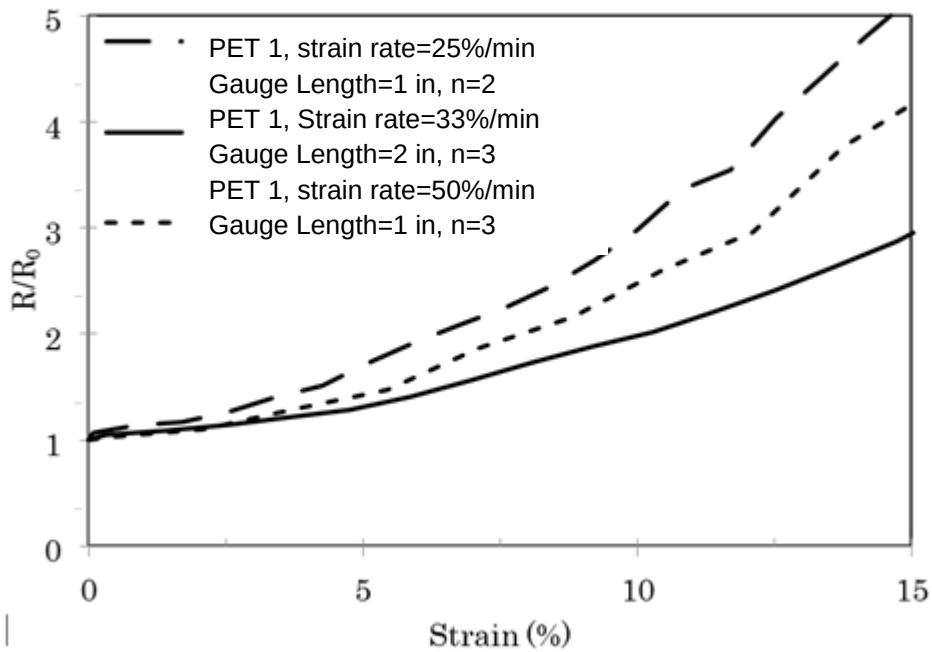

Figure 4. Tensoresistivity responses of graphene-coated PET specimens (product designation: s17061501) at different strain rates (25%/min - 50%/min), GL: Gage length, n: Number of trials

In loading to failure tests, the influence of gauge lengths on the specimens was also explored. For both testing and on-site data collection, the distance between the lead wires (i.e. gage length) needs to be standardized to get accurate, meaningful readings. From this test, calibration or conversion factors can be calculated for going from lab testing to field testing to keep data meaningful and consistent. For these additional tests until failure, the distance between the sensors on the sample was changed from one inch apart to two inches apart and the results were compared. The data are plotted in Fig 4, in which the one-inch gauge length trend line shows a greater change in normalized resistance (Which is the resistance divided by the initial resistance, or R/R_O) with increasing strain rate than the two-inch trend line. The strain rates used are 25%, 33%, and 50%. This can be explained as when the lead wires are closer to each other, fewer alternative pathways would exist for the electrical current to pass through between them when other paths are broken. Consequently, specimens show greater tensoresistivity response as the distance between the lead wires is reduced when other factors are kept the same.

4.2 Loading and Unloading Response

During these tests, the elasticity of the samples was explored at different strains and strain rates. The initial loading and unloading tests consisted of putting one specimen into the universal testing machine and stretching it to a target strain, then unloading until the force on the sample was zero pounds, then replacing the sample with a fresh one.

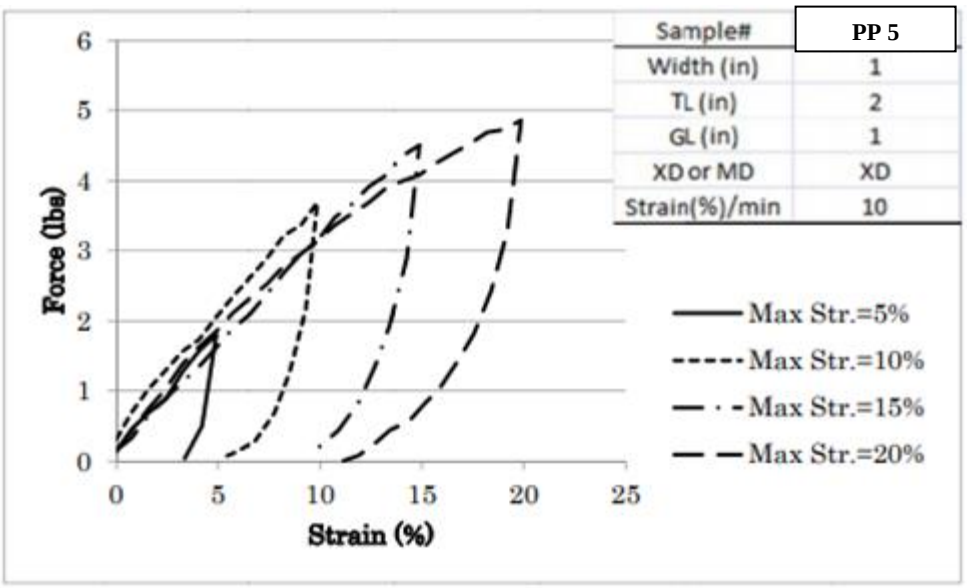

Figure 5. Loading/unloading performance of graphene-coated PP specimens; TL = total length, GL = gage length, XD = cross-machine direction, MD = machine direction (in production of the material)

The process was repeated until resistivity data were collected for strains of 5%, 10%, 15%, and 20% were collected, with new samples being introduced for each strain. The amount of strain a sample can take and still return to normal is its elastic limit, and this indicates that the sample was not damaged and the bonds were not broken. The results are plotted in Fig. 5 and show that all the samples behaved non-elastically because the force did not return to zero. Thus, the specific strains damage the sample to a point where it does not return to its original form, with both the polypropylene and polyester samples showing similar results.

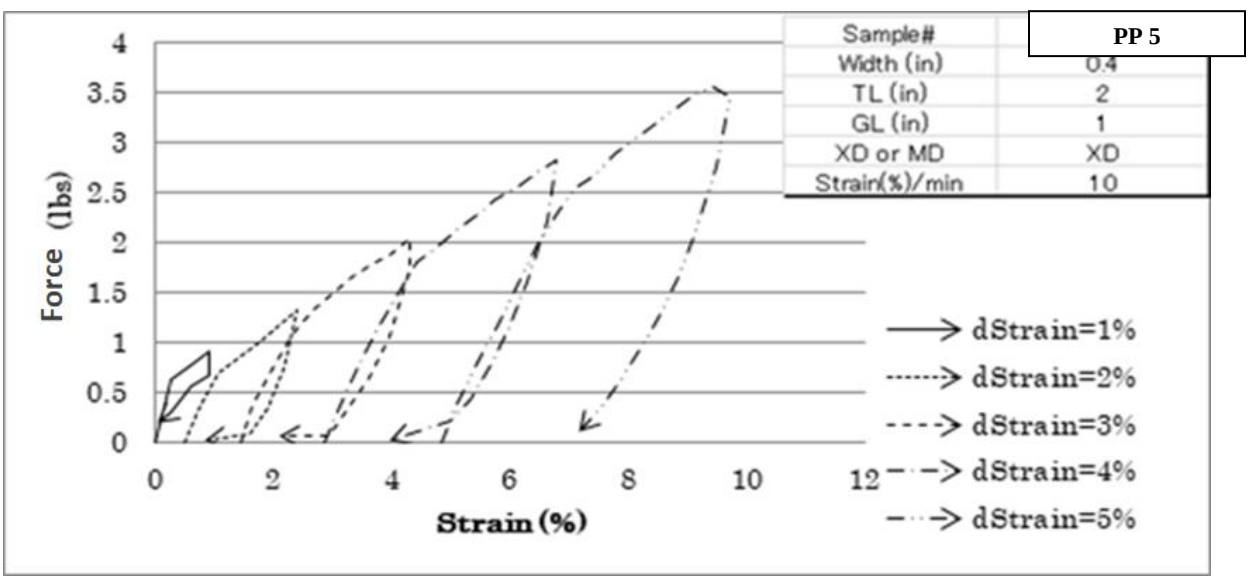

Figure 6. Loading/unloading performance of a graphene-coated PP specimen

An additional test was then performed to note how the sample reacted smaller strains, while having the sample undergo multiple strains one after the other in a cyclical pattern. For this test, the sample was kept in the universal testing machine and loaded to the target strain, and unloaded until the force was zero pounds. The process was repeated until resistivity data were collected for 1%, 2%, 3%, 4%, and 5% strains, all much smaller than the initial testing

strains. These are the maximum strains applied to the specimens. A strain rate of 10% was used throughout the experiments. The results are plotted in Fig. 6. The data show that even at these strains, both the polypropylene and polyester samples still show inelastic deformation, but on a smaller scale than the initial loading and unloading tests. The relationship between force and strain remained relatively consistent for each of the maximum strain rates achieved, with each cycle deforming to a similar degree relative to the maximum force applied. A somewhat linear relationship between maximum force and maximum strain for each loading cycle makes sense, as a larger force directly increases strain. Additional testing is required to find the maximum allowable extension where the material behaves elastically. These tests were conducted to see the behavior of the material under cyclic loads of stress, for example multiple cars driving over the same spot of road.

4.3 Twisting Tests

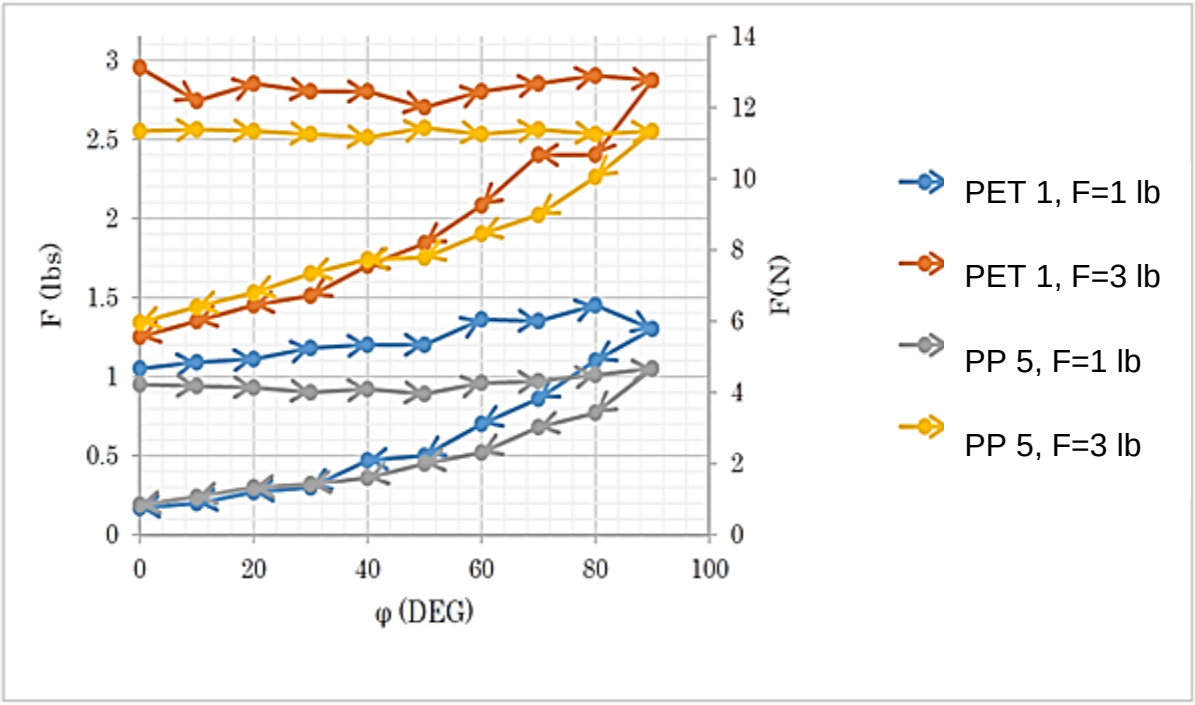

Figure 7. Mechanical performances of graphene-coated PET and PP specimens under twisting load

The twisting test aimed to quantify how different loads affect the samples when twisted at different angles. Each sample was put into the universal testing machine and twisted from 0 to 90 degrees, and back down to zero while resistance was measured at 10-degree intervals. The test was repeated with initial loads of either one pound or three pounds to quantify how loading damages the material. The results are plotted in Fig. 7 where the blue and grey trend lines had an initial load of one pound and the orange and yellow trend lines had an initial load of three pounds. The results from this experiment indicated plastic deformation, as none the samples returned to their original form or force after testing. This test was done to simulate instances of twisting in the field, for example tires applying pressure on a road adjacent to an area under less pressure.

4.4 Future Tests

Now that the behavior of the graphene coating under various directly-applied, tensile loads are better understood, the samples will need to undergo in-soil and indirect tensile loading tests to better simulate field conditions. In indirect tensile loading, the forces applied on a geotextile are spread throughout the material; this type of force application will be applied through the following test. The specimen will be layered over a rubber membrane and bolted into a square platform. Air will be pumped into the membrane and above the platform, applying pressure on the specimen. The resistance, deformation, and pressure under the membrane will be recorded. The in-soil test setup is still under development. However, in these future in-soil tests, the relationship between the conductivity of the soil and that of

the specimen needs to be studied. How does soil conductivity interfere with the specimen's changing conductivity? Soil conductivity could be comparable to that of the graphene-coated specimens, so this interference could be significant.

5. Results and Discussion

Results of all tests indicated that polypropylene (PP) samples were overall more consistent than polyester (PET) samples but less sensitive to strain. Although sensitivity is important, it was found that there are a few factors that increase sensitivity, which is believed to compensate for the reduced sensitivity in the polypropylene sample. One factor that increases sensitivity is using a lower strain rate, which is believed to better simulate field conditions, as standard strain at failure is 2-6%[4]. The other factor is having a smaller gauge length, which is why a standardized one inch gauge length was used throughout all experiments.

Future tests include in-soil tests, which will serve to simulate more realistic conditions, and will allow for the analysis of the conductive properties of soil and how they will affect the results of this experiment. In these future tests, both the electrical conductivity and water content of the soil must be standardized in order to get accurate results, as soil electrical conductivity is significantly influenced by the water content of the soil.[10] The effect of the soil conductivity will be explored with the deformation of the geotextile and compared to the results compiled from the tests done in this study. Additional testing to determine the elastic limit of twisting are planned, as well as loading tests. Because graphene bonds can't repair themselves, the elastic limit is how far the material can stretch with a negligible amount of graphene bonds being broken. Even though some deformation is expected in the field, knowing how much loading the material can take while remaining perfectly elastic is useful to know, which needs to be determined.

Overall, there is a significant relationship between resistance and deformation; however, more data are needed. There needs to be more experiments that provide data on how the material behaves in the field to determine if the tensoresistivity of the material is consistent enough to provide reliable data for practical applications.

6. Acknowledgements

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