



## Discussion

## “Laboratory tests on the engineering properties of sensor-enabled geobelts (SEGB)” by Cui et al., Geotextiles and Geomembranes 46 (2018) 66–76



Hessam Yazdani<sup>a,\*</sup>, Kianoosh Hatami<sup>b</sup>

<sup>a</sup> Department of Civil and Environmental Engineering, Howard University, 2300 Sixth St. NW Room 1026, Washington, DC 20059, USA

<sup>b</sup> School of Civil Engineering and Environmental Science, The University of Oklahoma, 202 W Boyd St. Room 450B, Norman, OK 73019, USA

### 1. Introduction

The article by Cui et al. is a significant contribution, given that it is challenging to design and fabricate sensor-enabled geosynthetics (SEG) that consistently exhibit reliable tensor resistivity performances in air and soil environments. The contribution of the work is that the strains calculated from the electrical conductivity measurements of SEGB specimens were nearly the same as those interpolated from strain gauge measurements.

While we commend the authors for the quality of their work, we believe that some aspects of sensor-enabled geobelts (SEGB), and of SEG in general, need further development and improvement before they can be implemented in practice. Additionally, we have identified areas in the paper that we believe further clarification and study details are warranted, and/or explanations provided may have to be reconsidered or revised, as we have discussed in detail in the following sections.

### 2. Experiments

The authors report the details and results of tensile, tensor resistivity (strain-sensitive conductivity) and pull-out experiments on three types of sensor-enabled geobelt (SEGB) specimens: 1) ‘laboratory-fabricated SEGB’, 2) ‘industry-fabricated, unsealed SEGB’ and 3) ‘industry-fabricated, sealed SEGB’, as summarized in Table 1. We discuss the experiments and comment on the observations made by the authors in the following separate sections.

#### 2.1. Materials, electrical conductivity and percolation behavior

High-density polyethylene (HDPE) and a ‘super conductive’ carbon black (CB) were used as the host matrix and the filler to produce SEGB specimens. No information was provided on the properties of the ‘super conductive’ CB. Such designations could be construed as commercial advertising and should be avoided in research papers because they are not associated with certain properties (e.g. surface area, oil absorption number and particle size) by which to estimate the structure and

percolation behavior of CBs. The structure of CBs is determined according to the particle size, aggregate size and shape of their primary particles, which could have considerable influences on their percolation behavior. Smaller primary particles have higher interaggregate attractive forces, resulting in a CB with higher structure and larger agglomerate size. A low-structure CB, in contrast, is formed when the aggregates are composed of few primary particles. Higher-structure CBs percolate at a lower concentration and produce a conductive network that experiences less damage upon loading, thus showing a relatively lower tensor resistivity but a greater degree of recoverability when subjected to dynamic loading (Hatami et al., 2014; Yazdani et al., 2014). The selection of the filler depends on the intended application of the final product. Time-varying loads applied on geosystems could progressively rupture the filler network within a SEG product and decrease its electrical conductivity and tensor resistivity. Overlooking this possibility could reduce the accuracy of the strains calculated using strain-conductivity regression functions developed in the laboratory.

Fig. 2 in the subject article shows the percolation behavior of the CB-filled HDPE composite where the CB concentration was expressed in terms of the mixing ratio of CB to the host polymer (i.e. HDPE). Such presentation is not accurate and could be misleading to a reader accustomed to the materials science and engineering literature where the filler concentration is customarily calculated in terms of weight/volume of the entire composite. The percolation threshold reported in the subject article agrees with previously-reported values (e.g. 45 wt.% by Nakamura and Sawa, 1998). However, as evident from Figure 12 in the subject article, such a relatively large concentration could considerably reduce the pliability of the final product, potentially making it prone to cracking and therefore, causing difficulties in its transportation and installation (Hatami et al., 2014). The flexibility of SEGB can be increased by adding a plasticizer to its formulation.

The authors deemed a visual inspection sufficient for assuring the quality of CB dispersion in the HDPE/CB blends. We argue that a visual inspection is not a reliable technique for dispersion evaluation because the color of a polymer usually rapidly turns to black even at small CB concentrations. In addition, the term dispersion generally refers to the nearly-uniform distribution of individual fillers in a matrix. However,

\* Corresponding author.

E-mail addresses: [Hessam.Yazdani@howard.edu](mailto:Hessam.Yazdani@howard.edu) (H. Yazdani), [kianoosh@ou.edu](mailto:kianoosh@ou.edu) (K. Hatami).

**Table 1**  
Summary of experiments in the subject article.

Specimen type	Laboratory-fabricated SEGB			Industry-fabricated, unsealed SEGB		Industry-fabricated, sealed SEGB	
Test environment	Air			Air		Soil	
Test type	Fast tensile	Slow tensile	Creep	Fast tensile	Slow tensile	Pull-out	Pull-out

this definition should be adjusted for nanocarbons (e.g. CB and graphene) that possess an inherent thermodynamic drive to aggregate with neighboring particles, and the resulting aggregates tend to entangle with neighboring aggregates to form agglomerates. Therefore, a dispersion state described as “uniform” or “good” for CB individuals in the aggregate scale might be a misleading or inaccurate description of their dispersion state in micro- or macroscale systems, where CBs are typically found in the form of agglomerates. In this regard, distinction should be made between nanoscopic dispersion, which refers to the disentanglement of individual CBs and more likely their aggregates, and micro- and macroscopic dispersion, which refers to the distribution of CB agglomerates throughout a composite. Our recent studies have shown that none of the conventional imaging techniques (e.g. SEM or AFM) is capable of characterizing filler dispersion in all instances and for all desired length scales, and a combination of different imaging techniques, each operating on a particular length scale, should be used for the multiscale visualization and dispersion assessment of fillers in composites (Smith et al., 2015; Yazdani et al., 2016b).

## 2.2. In-isolation tests on laboratory-fabricated SEGB

### 2.2.1. Fast tensile tests

Tensile tests on dog-bone-shaped specimens indicated 25% strength reduction across the percolation region and a smooth, linear reduction of strain at failure as the CB concentration increased. The authors attributed these observations to ‘inorganic’ CB particles diffusing the interspaces of HDPE molecules, thus weakening their connections and in turn the strength, ductility and strain at failure of the composite.

While the authors did not provide any references or microscopic images to support their inference, we believe that the authors' observations could be attributed to the reduced mobility of polymer chains. A given polymer often contains both amorphous and crystalline domains; e.g. 25% of HDPE could be made up of the amorphous domain where chains are not arranged in ordered crystals (Furukawa et al., 2006). This domain undergoes a state transition when the glass transition temperature  $T_g$  provides sufficient energy for segmental chain mobility, thereby changing the polymer's state from brittle (glassy) to ductile (rubbery). At the cure temperature, which is assumed to be initially higher than the glass transition temperature, CB particles/aggregates not only form covalent bonds with the polymer matrix but their high thermal conductivity facilitates the formation of a cross-linked, rigid network (i.e. polymerization). When the resulting composite is cooled down from its curing temperature, a phenomenon known as vitrification occurs. At the onset of vitrification, the glass transition temperature of the network approaches the cure temperature. Therefore, molecular mobility is reduced and chemical reactions are controlled by diffusion. Because of the competition between the formation of a rigid network, which depends on the segmental mobility, and the increasing glass transition temperature that impedes the mobility, the final material is a heterogeneous mixture of amorphous and crystalline domains. In case of a CB-filled polymer composite, the final material will have a higher glass transition temperature because its polymer chains will require a higher thermal energy for the onset of segmental motion compared to the pristine polymer. The increased glass transition temperature will consequently make the composite relatively stiffer and more brittle at room temperature (Rabilloud, 1997; Yoonessi et al., 2014).

The formation of zones of stress concentration around CB agglomerates within the composite could be another cause of premature

failure. Through the real-time microscopic imaging of carbon nanotube-filled polymers under increasing tension, we have shown that nanocarbon agglomerates in ductile host matrices can lead to a localized failure of the composite (Smith et al., 2015). Because the agglomerates are local and stiff sub-regions with a greatly increased CB concentration, stress becomes focused at these areas with its intensity being proportional to the stiffness (size) of the agglomerates. As tension increases, stress can grow sufficiently to rupture the largest agglomerates followed by smaller agglomerates in a fractal mode. As the specimen approaches failure, a large tear predominates at the site of one of the largest agglomerates and eventually fractures the specimen.

### 2.2.2. Slow tensile tests

In-isolation tensoresistivity of the CB-filled HDPE specimens was characterized through measuring the changes in their electrical conductivity values under tensile loading. Specimens doped at different CB concentrations around the critical (optimum) concentration (i.e. approximately 47.5 wt.%), which in the case of tension is the upper-bound of the percolation region, were fabricated and tested. The surface resistance at a given time during tension  $R_S$  normalized to the unstrained surface resistance  $R_{S0}$  was plotted against tensile strain to establish the tensoresistivity response of the specimens. The authors referred to the data point corresponding to 10% strain in Figure 6a to identify 47.5 wt.% as the CB concentration giving the highest tensoresistivity. We, however, suspect that the data point could be an outlier, and the test should have been repeated for validation. We base our supposition on the smooth 47.5 wt.% curve shown in Figure 10a.

The linear regression equations given in Table 2 of the subject article do not seem to be accurate. For example, substituting a value of 6% for strain in the linear equation of the 44 wt.% case will yield a value of 1.17 for normalized resistance which is much smaller than the value of 4.5 for the corresponding data point.

Let us define gauge factor as the relative change in a specimen's electrical resistance per unit strain as (Yazdani et al., 2014):

$$GF = \frac{(R_S - R_{S0})/R_{S0}}{\epsilon} \times 100 \quad (1)$$

where  $\epsilon$  is percent strain. Equation (1) gives a gauge factor of approximately 70 for the specimen filled with 44 wt.% CB. Put other way, the surface resistance of the specimen will increase 70% per 1% strain. This value seems to be inconceivably large for CB-filled composites, as the resulting gauge factor of 70 is more than one order of magnitude greater than those of typical commercial strain gauges (e.g.  $GF = 2$ ). However, the value is subject to decline if the composite undergoes a series of cyclic deformations. Since the conductive network within the composite consists of loosely connected CB particles and aggregates/agglomerates, frequent loading-unloading cycles could progressively break its structure and in turn decrease its conductivity and strain sensitivity (Yazdani et al., 2014). We suggest that the authors examine the tensoresistivity response of the composite under a variety of dynamic loads that are conceivable in practice.

### 2.2.3. Creep tests

The authors carried out in-isolation creep tests to study the long-term behavior of the composite under mechanical stress. Only the constant load (0.1 kN) was reported, and no information was given on the corresponding stress. Specimens containing a CB concentration in the range 44 wt.%–50 wt.% exhibited a similar creep behavior where primary (transient) and secondary (steady-state) creep stages were

evident. The secondary stage, where a balance between thermal softening and work hardening is established, is the most prominent creep stage under common stress conditions and should be controlled in practical applications. Out of the total creep strain of approximately 14% that was recorded in the tests, almost 5% occurred during the secondary stage. This value suggests that creep deformations of SEGB could be too large for geotechnical engineering applications where the strain at failure of soils is typically around 2%–6% (Hatami and Bathurst, 2005; Wanatowski and Chu, 2006). It is also one to two orders of magnitude greater than conventional creep strains of 0.5%–1.3% for geogrids (Hsieh et al., 2008).

### 2.3. Industrially-fabricated, unsealed SEGB

#### 2.3.1. In-isolation, fast tensile tests

Juxtaposition of Figures 4 and 9 of the subject article indicates that at a given CB concentration, industrially-fabricated, sealed SEGB specimens exhibited a similar strength but considerably lower strains at failure compared with their laboratory-fabricated counterparts. This difference could be due to the higher temperatures and more working zones that were used in an industrial extruder to fabricate the specimens.

#### 2.3.2. In-isolation, slow tensile tests

The industrially-fabricated, sealed SEGB specimens exhibited considerable tensorisitivity comparable to those fabricated in the laboratory. However, similar to Table 2, the regression equations given in Table 3 of the subject article do not seem to be accurate. For example, substituting a value of 10% for strain in the quadratic equation of the 45 wt.% case will yield a value of 3.76 for normalized resistance which is smaller than the value of 4.5 for the corresponding data point.

#### 2.3.3. In-soil tests

Specimens were tested under different confining pressures of 100 kPa, 200 kPa and 400 kPa. The same CB concentration of 45 wt.% was used in all specimens, and its corresponding correlation function was used to calculate strain from measured electrical conductivities. A series of strain gauges was placed on the specimens tested under 100 kPa confining pressure to confirm the accuracy of the indirectly-measured strains. The strain gauges had a maximum elongation of 2%, making it impossible to confirm the accuracy of the readings for stresses exceeding 50% of the front-end stress at failure and greater confining pressures. Nevertheless, a good agreement was observed between the strains measured using the strain gauges and those calculated from the correlation function. We should note that we expected to see the same results in Figures 16a and 18.

Given the paucity of data, it is difficult to confirm the accuracy of the correlation function over ranges of tensile stresses and confining pressures conceivable in practice. However, we presume that the in-isolation correlation function corresponding to a CB concentration may not be representative for in-soil conditions and different confining pressures. The confining pressure on a SEG layer reduces the thickness of the layer which in turn brings the CB particles and aggregates closer to one another. As a result, the SEG layer behaves as if it were filled at a greater CB concentration and therefore shows less strain sensitivity (Yazdani et al., 2016a).

Since the tensorisitivity of sealed SEGB was not reported, no comments can be made regarding the interference of the surrounding soil with the measured conductivities.

### 2.4. Industrially-fabricated, sealed SEGB

A jacket (hot pyrocondensation pipe - HPP) was adhered to SEGB specimens to examine its suitability for protecting SEGB from the

detrimental effects of installation damage and the surrounding environment. Results of pull-out tests on jacketed and unjacketed SEGB specimens were compared to examine strain compatibility at the SEGB/HPP interface. Expectedly, the jacket reduced the specimen-soil friction (sliding resistance), thus decreasing the pull-out strength. The authors referred to Figure 22 to confirm strain compatibility at the SEGB/HPP interface. We, however, believe that an appreciable slippage has occurred at the interface. If material A is tightly wrapped with material B, the stiffness and strength of the A/B composite are expected to be greater than those of A, unless the interfacial bonding/adhesion between the two materials is weak/imperfect. If that is the case, a sword-in-sheath fracture mode is conceivable where the wrapping material slides along the interface, thus questioning the strain compatibility of the two materials. Therefore, the residual stress and 'improved ductility' of jacketed SEGB reported in the paper are rather indicative of imperfections in the material that could seriously reduce the accuracy of measured strains.

### 3. Conclusions

Some points were made regarding the short- and long-term behaviors of SEGB in practice, their manufacturability in large scale and repeatability of the experiments. We suggest that the influence of strain rate and cyclic loading on the tensorisitivity response and mechanical properties of SEGB be investigated.

### References

- Furukawa, T., Sato, H., Kita, Y., Matsukawa, K., Yamaguchi, H., Ochiai, S., Siesler, H.W., Ozaki, Y., 2006. Molecular structure, crystallinity and morphology of polyethylene/polypropylene blends studied by Raman mapping, scanning electron microscopy, wide angle X-ray diffraction, and differential scanning calorimetry. *Polym. J.* 38, 1127–1136. <https://doi.org/10.1295/polymj.PJ2006056>.
- Hatami, K., Bathurst, R.J., 2005. Development and verification of a numerical model for the analysis of geosynthetic-reinforced soil segmental walls under working stress conditions. *Can. Geotech. J.* 42, 1066–1085. <https://doi.org/10.1139/t05-040>.
- Hatami, K., Hassanihah, A., Yazdani, H., Grady, B., 2014. Tensorisitive PVC coating for sensor-enabled geogrids. *J. Nanomechanics Micromech* 4 A4013016. [https://doi.org/10.1061/\(ASCE\)NM.2153-5477.0000070](https://doi.org/10.1061/(ASCE)NM.2153-5477.0000070).
- Hsieh, C.W., Lee, K., Yoo, H.K., Jeon, H., 2008. Tensile creep behavior of polyester geogrids by conventional and accelerated test methods. *Fibers Polym.* 9, 476–480. <https://doi.org/10.1007/s12221-008-0076-3>.
- Nakamura, S., Sawa, G., 1998. Percolation phenomena and electrical conduction mechanism of carbon black-polyethylene composites. In: Proceedings of 1998 International Symposium on Electrical Insulating Materials. 1998 Asian International Conference on Dielectrics and Electrical Insulation. 30th Symposium on Electrical Insulating Ma. Presented at the Proceedings of 1998 International Symposium on Electrical Insulating Materials. 1998 Asian International Conference on Dielectrics and Electrical Insulation. 30th Symposium on Electrical Insulating Ma, pp. 333–336. <https://doi.org/10.1109/ISEIM.1998.741753>.
- Rabilloud, G., 1997. High-performance Polymers: Chemistry and Applications. Éditions Technip. Paris, France.
- Smith, B., Yazdani, H., Hatami, K., 2015. Three-dimensional imaging and quantitative analysis of dispersion and mechanical failure in filled nanocomposites. *Composer Part Appl. Sci. Manuf* 79, 23–29. <https://doi.org/10.1016/j.compositesa.2015.08.019>.
- Wanatowski, D., Chu, J., 2006. Stress-strain behavior of a granular fill measured by a new plane-strain apparatus. *Geotech. Test J.* 29 (12621). <https://doi.org/10.1520/GTJ12621>.
- Yazdani, H., Hatami, K., Grady, B.P., 2016a. Sensor-enabled geogrids for performance monitoring of reinforced soil structures. *ASTM J. Test. Eval* 44. <https://doi.org/10.1520/JTE20140501>.
- Yazdani, H., Hatami, K., Khosravi, E., Harper, K., Grady, B.P., 2014. Strain-sensitive conductivity of carbon black-filled PVC composites subjected to cyclic loading. *Carbon* 79, 393–405. <https://doi.org/10.1016/j.carbon.2014.07.082>.
- Yazdani, H., Smith, B., Hatami, K., 2016b. Multiscale 3D dispersion characterization of carbon nanotube-filled polymer composites using microscopic imaging and data mining. In: Milne, W.I., Cole, M., Mitura, S. (Eds.), *Carbon Nanotechnology. One Central Press, Manchester, UK*.
- Yoonessi, M., Lebrón-Colón, M., Scheiman, D., Meador, M.A., 2014. Carbon nanotube epoxy nanocomposites: the effects of interfacial modifications on the dynamic mechanical properties of the nanocomposites. *ACS Appl. Mater. Interfaces* 6, 16621–16630. <https://doi.org/10.1021/am5056849>.