View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by epublications@Marquette

Marquette University
e-Publications@Marquette

Electrical and Computer Engineering Faculty Research and Publications

Electrical and Computer Engineering, Department of

7-25-2016

Standardized Testing of Non-Standard Photovoltaic Pavement Surfaces

John H. Nussbaum
Air Force Institute of Technology

Robert A. Lake
Air Force Institute of Technology

Ronald A. Coutu Jr.
Marquette University, ronald.coutu@marquette.edu

Accepted version. *2016 IEEE National Aerospace and Electronics Conference (NAECON) and Ohio Innovation Summit (OIS)*, (July 25, 2016). DOI. © 2016 Institute of Electrical and Electronic Engineers (IEEE). Used with permission.
Ronald A. Coutu, Jr. was affiliated with Air Force Institute of Technology at the time of publication.

Marquette University

e-Publications@Marquette

Electrical and Computer Engineering Faculty Research and Publications/College of Engineering

***This paper is NOT THE PUBLISHED VERSION;* but the author's final, peer-reviewed manuscript.**
The published version may be accessed by following the link in the citation below.

2016 IEEE National Aerospace and Electronics Conference (NAECON) and Ohio Innovation Summit (OIS), (July, 2016). DOI. This article is © Institute of Electrical and Electronic Engineers (IEEE) and permission has been granted for this version to appear in e-Publications@Marquette. Institute of Electrical and Electronic Engineers (IEEE) does not grant permission for this article to be further copied/distributed or hosted elsewhere without the express permission from Institute of Electrical and Electronic Engineers (IEEE).

Contents

Standardized testing of non-standard photovoltaic pavement surfaces

John H. Nussbaum
Department of Systems Engineering and Management, Air Force Institute of Technology, Wright Patterson AFB, OH
Robert A. Lake
Department of Systems Engineering and Management, Air Force Institute of Technology, Wright Patterson AFB, OH
Ronald A. Coutu
Department of Systems Engineering and Management, Air Force Institute of Technology, Wright Patterson AFB, OH

Abstract:

Emerging photovoltaic products have expanded the applications for the technologies into markets previously unconsidered for what was thought to be a delicate electronic product. One company leading this effort, Solar Roadways, Incorporated, is producing pavement replacing photovoltaic systems and proposing their use in everything from sidewalks to runways. Current pavement testing methods cannot be applied to these non-homogenous structures to identify if they can support the required loads. However, the standards called out specifically for pavements may be able to be translated to these products and their non-homogenous structures and non-standard materials to identify if they are able to perform similarly to standard pavements. This research modified existing test standards in several ways: rigid pavements standards for advanced loading, structural adhesive standards for shear loading, structure specific standards for moisture conditioning, and application specific standards for freeze/thaw cycling. These modifications are due to the fact that the materials in these emerging products do not have established tests to evaluate their performance in non-traditional applications. The future of electronics is dependent on product unique applications. This, in turn, requires finding methods of testing them based on application, extrapolation, or correlation to traditional material testing which enables faster product development and subsequent roll out.

SECTION I. Introduction

At an increasing rate, electronic products are being incorporated into devices and used for applications they previously had not been. In attempting to develop these products, material specific, standardized testing methods often do not include variations and adjustments for these nonstandard materials. While material specific testing standards are valuable in identifying the characteristics of each material, rapid prototyping can be accelerated by creating variations allowing testing on non-standard materials being used in a similar application. Alternatively, it can be done through the establishment of a set of test standards specific to the applications and anticipated real-world stressors rather than the materials. In this research, we will hypothesize methods for the application, extrapolation, or correlation of standard test methods to the Solar Roadways, Incorporated's SR3 model product to establish its performance characteristics. No current standards exist to identify if a glass and polymer laminate structure can endure the novel loads and stresses of a typical pavement. Therefore, standards will have to be used in nonstandard ways to evaluate the ability of this product and its materials to be used in a novel way in order to accelerate the product's roll out.

The Solar Roadways, Incorporated (SRI) SR3 Paver product is a modular system of reinforced photovoltaic pavers constructed of layers of tempered glass, polymer, metal, and composites with integrated electronic components. Because of its construction, it will be exposed to the same loads as a standard pavement, both environmental as well as static and dynamic. However, current standards to analyze paved surfaces are designed specifically for homogenously mixed materials such as Asphaltic Cement Concrete (ACC) and Portland Cement Concrete (PCC). These standards are well established and widely accepted through various governing bodies such as American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO), Federal Highway Administration (FHWA), Federal Aviation Administration (FAA), etc. For the purposes of this research, the focus will be on ASTM standards and how they can be used in non-standard methods to identify the metrics required of the SR3 product to compare to traditional pavements in an attempt to identify if it meets specifications of the FHWA and FAA.

SECTION II. Product Structure

A. Product Geometry and Construction

The SR_3 product is a hexagonal paver measuring approximately 26 “by 30” as shown in Fig. 1. There are half-pavers to allow for straight edges and quarter-pavers to allow for the corners of paved areas as well. Overall the unit is several inches thick and must be placed on a concrete foundation layer to provide continuous structural strength to the road. Other design characteristics are omitted due to their proprietary nature.

The tempered glass layers sandwich a central layer which contains all of the electrical, heating, photovoltaic, and computer processing components of each unit as shown in Fig. Fig. 2.[1] The electrical components within each paver unit are not internally powered by the pavers themselves. The photovoltaic cells provide power directly to the grid. The integrated LEDs, heat components, and computer processors pull power from the grid independently of those power production systems.

The polymer layer in the SR3 product is a harder, more temperature resistant product than used in previous models by SRI. Not only does this layer hermetically seal all of the climate sensitive components, but it acts as an adhesive, bonding the tempered glass layers into a laminated structure. It also transfers the loads from the bearing surface to the base glass layer which is in direct contact with the supporting concrete structure beneath the paver units.

Each paver is locked down to this concrete foundation layer with a series of vented clips along their edges. This method minimizes interference with the photovoltaic cells, maximizing the potential output of each panel. It also maintains a relatively smooth surface while still allowing for water to flow off the traversable surface. These vented clips allow for the flow of water away from the contact surface of vehicles and users of the pavement which lowers the risk of slick roads due to precipitation.

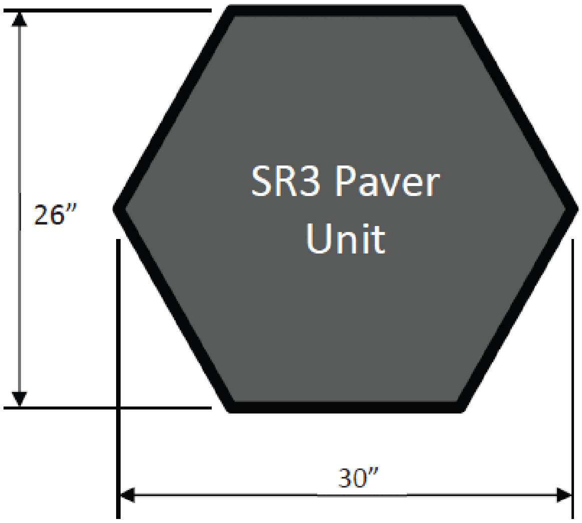

Fig. 1. Solar roadways, incorporated SR3 paver dimensions.

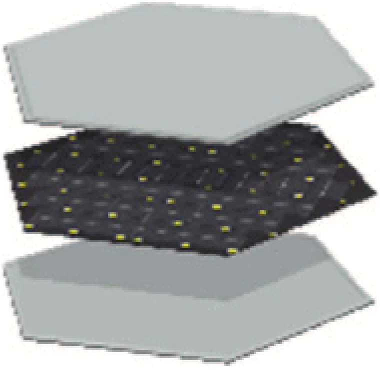

Fig. 2. SR3 paver layered construction.[1]

B. Product Components

The pavers contain multi-colored LEDs as shown in Fig. 3 which can be used to replace painted lines on roads, parking lots, or any other paved surface.[1] In conjunction with the computer processing capability, these could create smart roads that adjust their layout as required to allow for road hazards, safety concerns, specific parking requirements, early warning of approaching emergency vehicles, etc.

The pavers also maintain an integrated heating system which maintains them just above freezing temperatures to prevent the buildup of ice.[1] In conjunction with the vented clips, this capability eliminates the need for costly snow and ice removal operations while maintaining a safe transportation network. This will reduce municipal costs due to maintaining stocks of salt and deicing equipment as well as reduce individual costs from damage to personal vehicles caused by the road salt.

There are also load sensors which could be used to detect obstructions in the roads.[1] In conjunction with the computer processors and the LEDs, this could be used to alert traffic to hazards such as large animals, falling rocks, or collisions ahead before police and repair crews arrive to respond to the emergency.

The structural and hardware components are in final testing with funding from the Department of Transportation's (DOT) Small Business Innovation Research (SBIR) funding program.[1] The software components will require significant security programming and development and will likely be rolled out in phases. Allowing remote control of road markings will require significant risk analysis due to the potential for grid connected mass transit systems being hacked. Risks are lower for residential roads, parking lots, or sport courts. However, the remainder of this study investigates how to test this complex structure of non-standard materials for use as a pavement.

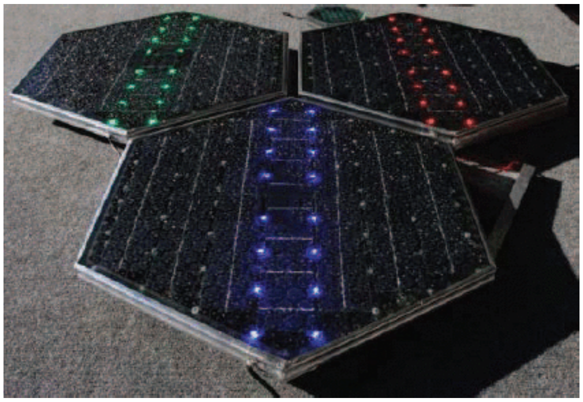

Fig. 3. SR3 LEDs shown in full daylight.[1]

SECTION III. Environmental Testing

A. DOT Required Testing

SRI has been awarded funding for Phase IIB under the DOT SBIR program. In this phase, SRI must perform Freeze/Thaw Cycling and Moisture Conditioning.[1] Due to the unique nature of the construction of the SR3 pavers and the materials they are made of, current standard pavement tests can not be directly applied. There are currently no standards that exist to directly evaluate a glass/polymer composite laminate structure to perform as a pavement surface. Therefore, existing standards must be applied in non-standard ways to identify the performance of the pavers as they would be influenced by stressors in real world conditions based on logical extrapolations of current standards. While there are numerous governing agencies for standardized testing, we will focus on ASTM active standards.

B. Freeze/Thaw Cycling

A key word search of the ASTM library of Active Standards reveals 134 active standards that reference “freeze-thaw” within them. These are generally broken down by material and product. For example, specifications are listed for “Concrete Aggregates,” and “Structural Clay Tiles,” and “Ceramic and Glass Tile.” In reviewing many of these, the method is nearly identical for the majority of the specifications. Generally, they require a specimen to be submerged in a solution and cycled through multiple freeze-thaw cycles before being visually analyzed for damage and weighed to determine any loss of material.

In identifying a standard most applicable to the unique geometry and intended use of the SR3 pavers, “C1645, Freeze-thaw and De-icing Salt Durability of Solid Concrete Pavers” seems most applicable.[2] Despite material differences, the intended use of the pavers is identical. Both concrete and SR3 pavers are intended for use on a paved surface. By analyzing the SR3 pavers in a manner identical to a concrete paver, a direct comparison can be made. Real world environmental conditions do not change simply because the materials being subjected to them do.

"C1026–13, Standard Test Method for Measuring the Resistance of Ceramic and Glass Tile to Freeze-Thaw Cycling" (which is materially more aligned to the product) specifies several procedures that misalign the specification from expected real world conditions that will affect the SR3 paver. First, it requires the specimens be cut to a specific size whereas C1645 tests full-size pavers.[2,3] Second, it requires that specimens be half-submerged in potable water where as C1645 requires full submersion and allows for a saline solution simulating deicing salts.[2,3] The specimens are cycled 300 times with no specification as to how long they must be kept in a frozen or thawed state whereas C1645 requires 16 hours of freezing and 8 hours of thawing for a single cycle with analysis being completed after 7, 28, and 49 cycles.[2,3] The analysis and report sections for both standards are nearly identical and require weights before and after as well as visual documentation of damage as compared to the pre-cycling condition of the specimen.[2,3]

Because of these differences in the standards, it can be seen that C1645 is a better standard than C1 026 to evaluate the anticipated real-world exposure conditions caused by freeze-thaw cycles to the SR3 paver unit despite that the standard is specified for concrete interlocking pavers. This non-standard application of C1645, when compared to C1026 which is specifically intended for products made of the materials of the SR3 paver is comprised, is found to have a more accurate set of test conditions and the analysis and reports required from both standards are nearly the identical.

C. Moisture Conditions

A similar key word search of the ASTM library reveals 1,026 active standards referencing "moisture conditioning." Whereas the freeze-thaw cycling is material and product specific, several of these standards are also application specific. For example, "Seamless Copper Tube for Air Conditioning and Refrigeration Field Service," and "Preformed High-Temperature Thermal Insulation Subjected to Soaking Heat," and "Water Absorption of Plastics." In reviewing many of these, the method is also nearly identical as found in the freeze-thaw standards. Generally, they require specimens be submerged in a solution after conditioning and then removed and weighed after specific periods of time. Many include a procedure that cycles the specimens through repeated submersions until the weight between measurements changes by less than a specified percent at which point it is considered that the effects further absorption are negligible.

In identifying a standard most applicable to the unique geometry and intended use of the SR3 pavers, "C272/C272M-16, Standard Test Method for Water Absorption of Core Materials for Sandwich Constructions" seems most applicable[4] though "D570, Standard Test Method for Water Absorption of Plastics" is more material specific.[5] C272 is designed to analyze the effects of water absorption of a permeable middle layer of a product between two impermeable layers for changes in the electrical and mechanical properties of the permeable middle layer. This aligns exactly with the structure of the SR3 product. Furthermore, it requires full submersion which is a realistic environmental condition the SR3 pavers must endure.

The primary deviation from this standard is that the specification calls for specimens of specific shapes and sizes.[4] Because the finished edge of the SR3 pavers incorporates metal clips protruding into the surface, testing on a completed paver will reveal more information about the penetration of water into the permeable layer. The standard does state that the specimen sizes are “recommended” but the specimen geometry is a requirement for testing. While standardized test specimens can be cut from a completed SR3 panel, it's likely that the results would be different than from a completed panel. Environmental testing, such as freeze-thaw cycling and moisture conditioning, should make efforts to be done in a manner as close to real-world conditions as possible.

D. Environmental Test Standards and Material Specificity

In reviewing the multitude of environmental test standards to find the most applicable ones for the DOT's SBIR Phase IIB funding for SRI's SR3 paver units, it is clear that the methods for the majority of standards intended to evaluate the effects of specific conditions are nearly the same despite being broken into material and/or application specific standards. It's arguable that there's no need for 134 standards to test the effects of freeze-thaw cycling, nor 1,026 for the effects of moisture conditioning. As stated above, the environmental conditions do not change simply because the material does. It's logical that a singular standard for the method of exposing products to specific environmental conditions could be generated for each expected condition. From this standard, a uniform series of standards could be established with an analysis methodology resulting in consumers being able to identify the products performance along specific common metrics. This would allow a more direct comparison of the performance of various materials and products in specific environmental conditions under a singular system of evaluation which would enable much faster product development.

An observable trend is currently taking place amongst the handheld electronics industry with the Ingress Protection (IP) Coding system. This system is uniform regardless of materials or construction and allows a direct comparison of the dust and water penetration resistivity of any handheld electronic device.[6] Arguably, a similar system could be established for all environmental conditions with each industry determining what level of performance must be achieved for specific applications of emerging products and technologies. For example, the water resistance of a product intended for use as a pavement must be IPXX or greater on the IP Code system.

SECTION IV. Applied Load Testing

A. DOT Required Testing

In addition to the environmental testing previously mentioned, the DOT's SBIR Phase IIB funding to SRI for their SR3 paver unit required Shear Testing and Advanced Loading. Again, due to the unique construction of the SR3 pavers and their component materials, standard pavement shear and load testing methods are not directly transferrable to the product in most cases. The SR3 paver, due to its mixture of both rigid tempered glass and flexible polymer layers, blends the concerns of both rigid and flexible pavements.

Both ACC, or “flexible,” and PCC, or “rigid,” pavements transfer their loads in different manners. A flexible pavement is essentially a waterproof membrane over an engineered soil which bears the load of the traffic whereas a rigid pavement bears the load directly. Because of this, the load resistance of ACC pavements is allowably lower than PCC pavements. In flexible pavement design, shear loads are a great concern as damage caused by vehicle breaking and turning can rip the pavement and extreme temperatures can cause the pavement to become brittle and crack or re-liquefy and push out from under traffic. These damages expose the engineered soils leading to erosion which reduces the structural strength of the road. Rigid pavements, once poured to their design thickness, resist shear loading without great concern though erosion caused by cracks and seams still represents the same concerns. The nature of the SR3 paver's materials and construction standard prevents pavement testing, specifically the common Superpave Shear Tests, from be performed on the product for shear testing. Furthermore, there are no existing tests for complex glass/polymer composite laminates to measure their performance equivalently to rigid pavement tests.

B. Shear Testing

As with the environmental testing, a key word search of the ASTM Active Standards database reveals 867 active standards referencing “shear strength.” These cover a broad spectrum of potential conditions in which shear strength is a critical metric such as for “Structural Adhesives,” “Thick-Adherend Metal Lap-Shear Joints,” and “Bearing Response of Polymer Matrix Composite Laminates.” However, as with the environmental tests, many of the specifications for shear testing are centered around a nearly identical test procedure. The test specimen is mounted in a piece of equipment that can either apply tension or compression at a steady, measured rate. Sensors are applied to the test specimen and it is either pulled apart or pushed along parallel axes until failure.

In reviewing those standards for polymer composite laminates, they specify that they're either for fiber-reinforced laminates or thin composite laminates and the test equipment pulls the specimen along a single axis. When considering the unique construction of the SR3 paver unit, the forces introducing a shear load would be along the wearing surface of the top glass layer. This means that the polymer layer can be equated to a thick adhesive between two tempered glass adherends which must hold the structure together when shear forces are introduced to the wearing surface.

There are specific tests for shear testing of adhesives. The most applicable, given the thickness of the glass adherends, appears to be “D5656-10, Standard Test Method for Thick-Adherent Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading”.[7] As shown in Fig. 4 pulled from the standard, this specification allows the identification of the stress-strain relationship of an adhesive, not it's adhesion to the adherend, as it is put in tension between thick adherends.[7]

In order to evaluate the adhesion of the polymer to the glass adherends, “D4027, Measuring Shear Properties of Structural Adhesives by the Modified-Rail Test” seems most applicable.[8] Whereas D5656-10 evaluates the stress-strain relationship of the adhesive itself in tension which is a critical metric given the thickness of the polymer layer in the SR3 paver, D4027 specifically measures the “bond shear strength determined as the shear stress at failure” of the adhesive.[8] Note 1 of the specification states that “common construction materials may also be used for adherends” allowing the use of the tempered glass to directly measure the polymer's adhesion to it.[8] As shown in Fig. 5, the specimen for this test places the two adherends into rails that pinch them while a force is applied parallel to the adhesive's axis causing the exact alignment of forces as would happen in real world applications of the SR3 paver.[8]

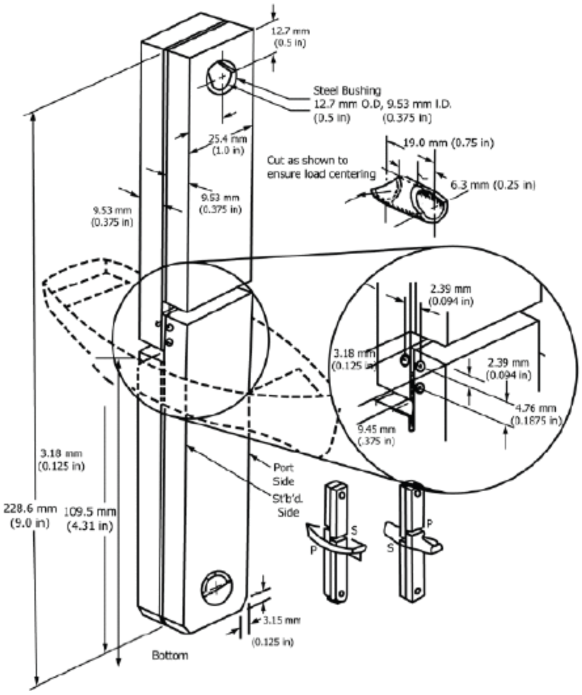

Fig. 4. Test specimen preparation diagram for D5656-10.[7]

One limitation of this standard is that the adhesive layer thickness is limited to 0.5" maximum.[8] Therefore, custom test specimens would have to be manufactured or it would have to be applied in a non-standard method. However, should the maximum thickness be exceeded, it's likely that the loading would be transferred from the bond between the polymer and the tempered glass to polymer itself. This may cloud the results as the maximum shear load achieved would be resisted by both the adhesion and the shear strength of the polymer combined rather than purely the adhesion. This may find the specific shear strength of the unit, but additional testing will have to be done to identify the shear strength of the clips beyond the scope of this line of paver specific research.

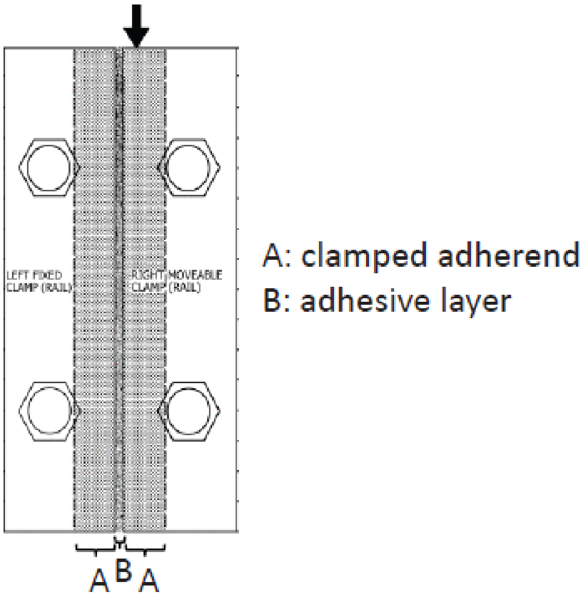

Fig. 5. Test specimen preparation diagram for D4027.[8]

What both of these shear methods disregard is the effects of the geometry of the hexagonal paver on the resistance of shear forces. Though the forces may be applied in a generally linear way during breaking and accelerating, they can also be applied in any number of directions or changing in direction and the top layer of glass will disperse that force over a larger surface area than the linear test specimens in these specifications allows. “D4255M-15a, Standard Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method” [9] may allow for this if applied in a non-standard method.

The three-rail method allows the testing of a panel of a material for its shear properties. The specimen is intended to be prepared as shown in Fig. 6 with a maximum thickness of 0.125”.[9] However, if we disregard the specimen specifications and simply machine an entire SR3 paver unit to attach the three-rail fixture as shown in Fig. 7, we can measure the shear strength of the unit as a whole.

In order to attach the SR3 paver panel to the three-rail test fixture, notches would have to be cut all the way through the glass and polymer layer on alternating sides of the paver as shown on cross-sections A-A and B-B in Fig. 7. Additionally, bolt holes would have to be drilled through the remaining glass layer to allow attachment of the fixture itself. The dimensions of these notches and the layouts of the holes would have to allow the fixture to be attached tightly but without pinching. There are noted variations in the specification allowing for alternate methods of attachment of the rails depending on the material being attached including more bolts, sandpaper, and adhesives.

Though this is an extreme modification of the test standard's specification for test specimens, it would allow direct analysis of the total shear strength of the paver to resist shear loads induced by traffic on its surface. Across all of the various methods of shear testing, there are a few apparati used and a few methods by which the force is applied. However, they all equate to attaching the test specimen to fixtures consisting of rails either pinching or bolted to the fixture and pushing or pulling the two rails in opposing directions. This same generalized method of applying the force is then broken out into numerous specifications for various materials and applications. Though there are a few variables that may be measured through this loading method such as the stress-strain relationship of the polymer layer itself versus the adhesion to the adherends, the methodology is nearly the same.

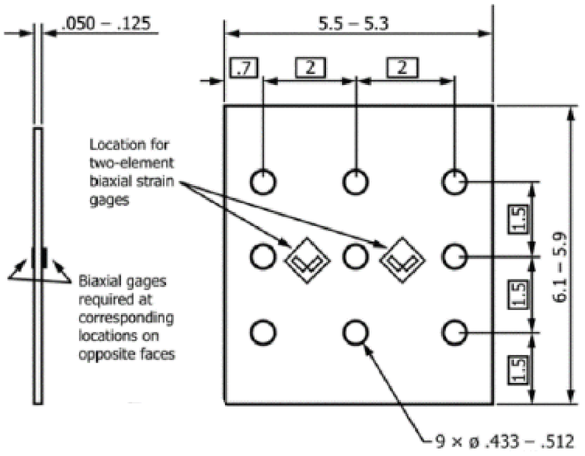

Fig. 6. Test specimen preparation diagram for D4255M-15a.[9]

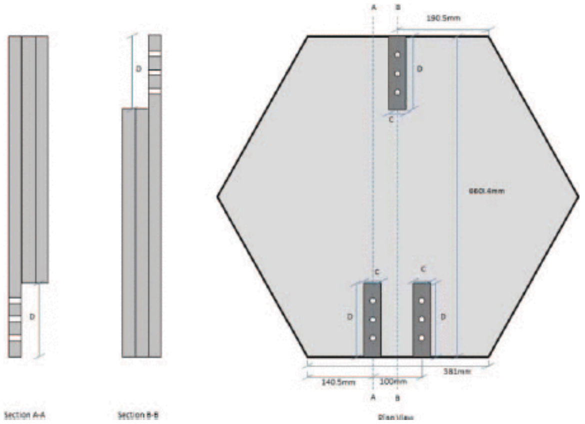

Fig. 7. Non-standard test specimen preparation diagram for D4255-15a.

Because of the universality of the application of forces, efforts towards simplification of these standards could be made in a similar manner to how the Environmental Testing standards are proposed to be simplified above. A universal three-rail specification could be established, regardless of the material, with test specimen standards for determining specific material characteristics and different test specimen standards for determining specific product characteristics. The same could be done for the two-rail method and any other method based on the fixture used to test the material or product. The researcher conducting the test would have to pick which fixture best applies for the specific metrics they desire and the specimen they want to evaluate, but given that there's a limited number of fixtures and methods, the entire library of 867 standards might be able to be simplified down to a handful.

C. Advanced Loading

Advanced Loading, for pavement testing, is most typically done with a “Dynaflect” or “Road Rater” apparati in accordance with “ASTM Active Standard D4602-93(2015), Standard Guide for Nondestructive Testing of Pavements Using Cyclic-Loading Dynamic Deflection Equipment” which can be done directly to the SR3 pavers with no variation despite the standard not reflecting glass/polymer laminates as a standard test specimen.[10] However, neither of these apparati are available to this research team. Existing point load testing and impact resistance has been completed on the tempered glass surface of the SR3 paver unit, from which it was identified that it's performance was satisfactory for DoT standards. One area that the product has not been vetted for is use on airfields which is a very value-added application for this technology given the volumes of potential represented on site.

In researching airfield construction standards, the FAA currently uses the FAARFIELD Airport Design Software package as its standard pavement design methodology, which available for free from www.faa.gov.[10] In order to use this software, the only variable for the pavements that must be known is the Modulus of Elasticity. This can be tailored for the concrete based on the mix and additives and can be evaluated for the SR3 paver based on existing standards in the same way airfield rigid pavement mixtures have their Modulus of Elasticity determined. If we conceptualize the SR3 pavers to be a non-bonded rigid overlay by definition, we can use existing methodologies to design with the pavers as the surface of the airfield pavement.

UFC 3-260-02, Chapter 9, Paragraph 3.e.(1) specifies that military airfields are to be designed based on the three-point flexural beam test per ASTM C78.[12] This standard's application of the three-point flexural test methodology is nearly identical to that of Active Standard “D7264, Flexural Properties of Polymer Matrix Composite Materials” as showing in Fig. 8.[13] D7264 can be used to evaluate the SR3 paver as it specifically sates in paragraph 5.5 that it “may also be used to determine flexural properties of structures” and the results of this standard reveal the Flexural Modulus of Elasticity.[13]

This test specification, as with most of those specifying the use of the three-point loading fixture, requires the test specimens to be cut into specific ratios of dimensions. This is feasible with the SR3 paver using a diamond bladed band saw to cut through the entire cross section at various points to create multiple test specimens to account for variations in the electrical components in the polymer layer causing differences in the overall strength of the paver.

This standard reveals the one variable needed to use the FAA's FAARFIELD standard software for pavement design with the unknown variable being the rigid pavement underlay. Additionally, this software allows design with multiple layers in the pavement cross section so it could theoretically be modified to identify the strength of the surface if the SR3 pavers were to be placed directly on top of the existing pavement profile.

Alternatively, we can potentially use existing airfield pavement design equations to hand calculate the required thickness of the concrete layer beneath the SR3 pavers. If preferred over using the FAARFIELD software design package, (1) provides the calculation for a non-bonded, rigid overlay of a rigid pavement. This equation matches Equation 17–3 from UFC 3-260-02.[14]

$$h_o = \sqrt{h_d^2 - C\left(\frac{h_d}{h_e} * h_E\right)^2} \tag{1}$$

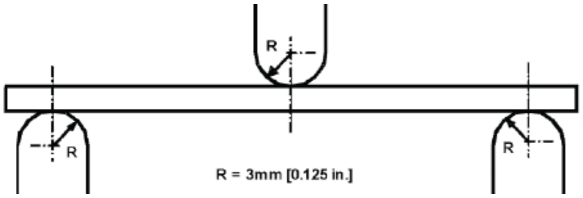

Fig. 8. Three-point loading methodology diagram.

o	= new overlay thickness (SR3 paver thickness)
	= pavement thickness if full cross section were made of material with empirically determined flexural strength of the overlay (if SR3 paver placed directly on subgrade, how thick would it have to be)
e	= pavement thickness if full cross section were made of material with the measured flexural strength of the underlay (if existing pavement were thickened to meet design requirements, how thick would it have to be)
E	= existing underlay thickness
	= Condition Coefficient of Existing Pavements (reference UFC 3-260-02, Chapter 17, Paragraph 5.b.)

As h_o and C are known or can be identified from tables, the only variables are h_d and he which can be found with (2), which is Equation 12–1 from UFC 3-260-02, and calculates a pavement thickness over a stabilized base and/or subgrade.[14]

$$h_o = \sqrt[1.4]{h_d^{1.4} - \left[\left(\sqrt[3]{\frac{E_b}{E_c}}\right) h_b\right]^{1.4}} \tag{2}$$

o	= pavement thickness (h_d or he for Eqn (1))
d	= design thickness if full cross section were made of in situ stabilized base as identified in the design curves in UFC 3-260-02, Chapter 12
b	= Modulus of Elasticity of the stabilized base
c	= Modulus of Elasticity of the pavement (SR3 paver for h_d or existing concrete for he)
b	= thickness of stabilized base

Using these equations, we can calculate h_o from (1) which equates to the minimum required thickness for the SR3 pavers. So long as the pavers are thicker than this minimum, they suffice as a non-bonded overlay of the rigid pavement. There are other versions of these equations should the products be considered partially bonded, involve flexible pavements, or other possible variations to these assumptions and conditions.

Regardless of how the pavement design is completed, the critical variable is the Modulus of Elasticity which can be found from D7264 which specifies the three-point loading test which is nearly identical to the required test for airfield pavements from C78 which is the required standard for pavement thickness design per UFC 3-260-02.

D. Applied Load Test Standards and Material Specificity

As with the Environmental Test Standards, the Applied Load test standards are broken out into seemingly unnecessarily material specific categorizations. This is exacerbated in this case by the fact that there are a limited number of standardized fixtures with which the loads can be applied. These fixtures can only be attached to the test specimens in a limited number of ways. Therefore, it is feasible to break out these specifications into fixture specific test standards based on the desired variables such as “Flexural Strength Testing using the Three-Point Loading Method” or “Shear Strength Testing using the Three-Rail Loading Method.” This would reduce the total number of test standards greatly, simplifying the overall process of product testing.

These specifications could contain recommendations based on subjective material characteristics such as brittleness or flexibility, thin or thick specimens, laminates or homogenous specimens, but should not reference the materials being tested. This would allow direct comparison of various materials for specific applications, eliminating the struggle to find appropriate test standards for materials being used in novel manners.

SECTION V. Standardized Testing of Non-Standard Photovoltaic Pavement Surfaces

Traditionally, photovoltaic surfaces are non-trafficked surfaces. They have not historically been designed to be required to be safe for pedestrians, vehicles, aircraft, or frankly anything except precipitation and dust to rest on their surface. For this reason, they've been designed specifically to protect the photovoltaic cells beneath the surface. This emerging market of photovoltaic pavement systems necessitated a need to conduct entirely different testing on photovoltaic structures.

Existing test standards are generally written specifically for traditional materials being used in relatively common manners within certain industries. When materials are to be used in novel ways, there are not existing test standards to evaluate their safety or performance. For this reason, existing test standards must be adjusted in one of several ways to identify if a product made of novel materials can be used safely in novel manners. The standards may be implemented directly, without variation, as the material from which a product is made does not affect the manner in which natural stressors are applied. Alternatively, standards using the same application of forces as expected in real world scenarios, but not matching those used for traditional materials, may be used and the resulting analysis can be done to identify the same characteristics as traditional material tests. Otherwise, standards using the same test fixtures may be used as those standards used on traditional materials.

In reviewing this requirement to vary standardized tests or find equivalents for non-standard materials, it's clear that many of the material specific divisions in ASTM testing standards are unnecessary as the methodologies and analyses between them are nearly identical. It may optimize the library of standards if material specific divisions were eliminated. Test standards should be established based on the stressors the product must endure for environmental testing or based on the fixtures and/or application of loads for applied load testing. This seems to be a feasible adjustment of the library of standards if it's acknowledged that the application of stressors and forces does not change simply because the material does. This simplification of the library of standards could reduce the time to market for product development significantly as direct comparisons are more feasible. Researchers and experts from specific fields and industries could identify performance specifications, as many already do, for products intending to be used within their area of field.

Material specific testing is still a value added line of research as it identifies specific material characteristics. This can be used to optimize product designs and rule out specific materials from use for certain applications due to safety or other concerns.

ACKNOWLEDGMENT

The authors would like to thank Scott and Julie Brusaw who shared information and helped in the scoping of this line of research.

References

1. S. Brusaw, J. Brusaw, Solar Roadways: A Real Solution, Solar Roadways, Incorporated, [online] Available: http://www.solarroadways.com/.

2. C1645/CI645M-11 Standard Test Method for Freeze-Thaw and De-icing Salt Durability of Solid Concrete Interlocking Paving Units, ASTM International, 2011.

3. C1026–13 Standard Test Method for Measuring the Resistance of Ceremic and Glass Tile to Freeze-Thaw Cycling, ASTM International, 2013.

4. C2 72/C2 72M-16 Standard Test Method for Water Absorption of Core Materials for Sandwich Constructions, ASTM International, 2016.

5. IP Code, Wikimedia Foundation, [online] Available: https://en.wikipedia.org/wiki/IP_Code.

6. D5656–10 Standard Test Method for Thick-Adherend Metal Lap-Shear Joints for Determination of the Stress-Strain Behavior of Adhesives in Shear by Tension Loading, ASTM International, 2010.

7. D4027–98(2011) Standard Test Method for Measuring Shear Properties of Structural Adhesives by the Modified-Rail Test, ASTM International, 2011.

8. D4255-D4255–15a Standard Test Method for In-Plane Shear Properties of Polymer Matrix Composite Materials by the Rail Shear Method, ASTM International, 2015.

9. D4602–93(Reapproved 2015) Standard Guide for Nondestructive Testing of Pavements Using Cyclic Loading Dynamic Deflection Equipment, ASTM International, 2015.

10. Airport Design Software, Federal Aviation Administration, [online] Available: http://www.faa.gov/airports/engineering/design_software/.

11. "Unified Facilities Criteria (UFC) 3–260-02 Pavement Design for Airfields", [online] Available: https://www.wbdg.org/ccb/DODIVFC/ufc_3_260_02.pdf.

12. D7264/D7264M-07 Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials, ASTM International, 2007.

13. D570–98 Standard Test Method for Water Absorption of Plastics, ASTM International, 2010.

14. C78/C78M-15b Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading), ASTM International, 2015.