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Original Paper

Testing Photovoltaic Pavers for Roadway Applications

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Abstract

Concrete and asphalt are the primary materials used to construct roadways for motor vehicles, bike paths for pedestrians and bicyclists, and runways for aircraft. Solar Roadways®, Inc. (SR) in Sandpoint, ID, proposed using robust, Solar Road Panels (SRPs) as an alternative roadway material due to the potential for creating a modular, multi-functional infrastructure product with cost-savings, user-safety, power-generation, and a better alternative in terms of environmental sustainability when compared to contemporary pavement materials. Typical roadway construction materials, on average, need to be replaced every 10-15 years while also requiring regular annual maintenance to maintain proper safety standards. SR's novel roadway material is intended to extend roadway replacement timelines, lower annual maintenance costs, and provide energy to the power grid. In this study, we tested the mechanical properties of the "SR3" model prototype SRP and evaluated its suitability as a replacement roadway material with the added benefit of generating electric power. Specifically, we tested this unique pavement material in submerged water environments, under extreme temperature conditions, and under dynamic loading conditions.

Keywords

solar, roadways, moisture testing, shear testing, heavy vehicle simulation testing, power generation, renewable energy, environmental sustainability

1. Introduction

In recent years there has been a global demand to use sustainable technologies which not only meet current power generation needs but also ensures that future power generation demands are met (Uzarowski & Moore, 2008). The phenomena of the greenhouse effect or global warming is a highly debated topic today on domestic and international platforms. These debates increase awareness about the need for sustainability in the environment. People, industry, and governments are increasingly giving consideration to the environmental effects of the materials used in paving roadways. Thousands of miles of roads are paved every year using traditional materials like asphalt or steel-reinforced concrete (Alkins et al., 2008; Bocci et al., 2011; Bowers et al., 2015; Diefenderfer et al., 2015; Gerbrandt et al., 2000; Gu et al., 2015; Gu et al., 2019; Grilli et al., 2012; Horvath & Hendrickson, 1998; Miliutenko et al., 2013; Stimilli et al., 2013; Thenoux et al., 2007; Polston, 2004).

In addition, the importance of energy security cannot be understated in today's global economy and need for increased national security. Decentralized power production and micro grids are far more secure and sustainable methods of power production, as compared to any centralized power source, even centralized solar arrays. These traditional photovoltaic based renewable energy systems require that large swaths of land be dedicated to power generation. SR's Solar Road Panels shown in Figure 1, will enable photovoltaic-based power production in readily available areas, which have already been removed from wilderness (i.e., roadways, sidewalks, parking areas, driveways, etc.) where vast amounts of available surface area outweigh the power production efficiency of any single panel.

2. Manufacturing Process—"SR3" Prototype

The "SR3" prototype Solar Road panels were manufactured by SR using a proprietary process consisting of hexagonal tempered glass plates, photo Voltaic (PV) cells mounted on a custom circuit board, and a novel polymer adhesive layer. The entire structure was laminated together, with the top surface being fused with a novel polymer adhesive layer, resulting in an engineered rough surface designed to increase the glass surface's coefficient of friction to prevent slipping. In addition to the solar power capability, the "SR3" prototypes contain Light Emitting Diodes (LED), and an internal heater circuit. The LEDs and heaters are intended to eliminate the need for painting roadways and reduce snow removal efforts in colder climates. An image of three of the SRP prototypes is shown in Figure 1. An insulated electrical cable was imbedded in each paver and used to electrically connect each panel to the control circuit which enabled monitoring and control (Brusaw, 2016).

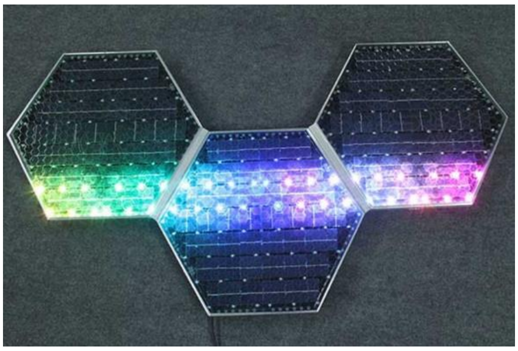

Figure 1. Solar Roadway, Inc. "SR3" Paver Panel (Brusaw, 2016)

3. Test Methodologies

Three tests were conducted to examine paver performance in wet environments, during repeated freeze-thaw cycles, and under dynamic loading conditions. The tests were conducted to investigate the mechanical properties and basic operation of the SRPs. The results were intended to show that the SRP prototypes behave in accordance with recognized Department of Transportation (DOT) and Federal Highway Administration (FHWA) safety standards. The tests were performed in accordance with recognized industry practices and standards as provided by the American Society for Testing and Materials (ASTM). Special considerations were made to ensure that the tests were similar to tests performed on rigid pavement surfaces. Necessary modifications to the standardized testing, due to the unique nature and/or geometry of the SRPs, were documented. Testing was performed on the Marquette University (MU) campus in the Engineering Materials and Structural Testing Laboratory (EMSTL). Electrical testing conducted at Marquette consisted of verifying LED functionality. The SRP heaters were not explicitly tested. The SRP control software was set to activate the heaters at 3 ℃ and all tests were conducted in either a controlled 22 ℃ laboratory environment or outdoors with temperatures above 15 ℃.

3.1 Moisture Conditioning Duration

The moisture conditioning duration test was conducted to investigate the mechanical properties and operation of the SRPs under wet conditions. The SRP glass surfaces represent impermeable surfaces so that moisture has a limited effect. Therefore, the moisture conditioning test was primarily to evaluate the exposed polymer layer between the impermeable glass plates. The ASTM Active Standard D570-98(2010) e1, "Standard Test Method for Water Absorption of Plastics", was used to evaluate the effects of water absorption or humidity exposure of the polymer layer (ASTM Standard D570-98(2010) e1, 2014). This test method was intended to determine "the relative rate of absorption of water by polymers when immersed and applies to all types of polymers, including cast, hot-molded, and cold-molded resinous products, and both homogeneous and laminated polymers in rod and tube form and in sheets 0.13 mm (0.005 in.) or greater in thickness". The test has two primary objectives: first, to identify the proportion of water absorbed by the polymer material and second, to identify the effects of exposure to water or humid conditions on the properties of the polymer material such as electrical, mechanical properties and on dimension, appearance, etc.

Moisture absorption affects the water content of the polymer and is directly related to electrical conductivity, mechanical strength, dimension, and physical appearance. The amount of absorption depends greatly on the type of water exposure (i.e., immersion or exposure to high humidity), the shape, and the properties of the polymer. The moisture testing was conducted on full-size SRPs not small test samples as described in the ASTM Active Standard.

The moisture conditioning testing was accomplished using a single 300-gallon aluminum tank where all three pavers were simultaneously submerged with enough water to cover the pavers completely with approximately one-inch of water above the paver's surface. This ensured that a constant water pressure was exerted on each of the pavers throughout testing. Figure 2 illustrates paver position and spacing in the tank. Also shown in Figure 3 is the wire and connector placement above the waterline during testing.

Figure 2. Single 300-Gallon Aluminum Container Used during the SRP Moisture Conditioning Duration Testing. The Paver Electrical Connectors Were Fixed above the Waterline during Testing

Figure 3 shows the weigh system used for the SRPs.

Figure 3. Test Apparatus for Weighing the SRPs before and after each Moisture Conditioning Test

Three SRPs, supplied by SR (S/N's 3A-3C), were baseline tested (i.e., electrically and weighed) and then subjected to long duration moisture testing as follows: 1) a 24-hour test, 2) a seven-day period, 3) a 14-day period, and 4) additional 14-day periods as needed. The pavers were submerged for the required time period(s), removed from the water tank, dried with a lint-free towel, weighed, and then moved for electrical testing (i.e., LED functionality). The apparatus for weighing the pavers was constructed from wood and the following steps were followed to mitigate any negative effects: 1) the fixture was stored in the temperature-controlled EMSTL at Marquette the entire time, 2) for every measurement the pavers were dried with a lint-free cloth prior to being placed on the test jig, and 3) the scale was tarred with the fixture weight prior to the test pavers being placed on the jig and weighed. Once electrical testing was complete, the pavers were again weighed and placed back into the water tanks to begin the next test cycle. Moisture testing was accomplished until the measured weight increase, after three consecutive weigh-ins, was less than 0.1% of the total paver weight or 5 grams, whichever was greater.

3.2 Freeze/Thaw Cycling

Temperature extremes are contributing factors to roadway material failures. The SRPs consist of laminate material sandwiched between glass layers. Since the glass and laminate materials have different Coefficients of Thermal Expansion (CTE), cycling the panels through temperature extremes was done to evaluate SRP mechanical and electrical functionality in real-world conditions.

We modeled our unique testing after ASTM Active Standard C1645/C1645M, "Standard Test Method for Freeze-thaw and De-icing Salt Durability of Solid Concrete Interlocking Paving Units" (ASTM Standard C1645/C1645-15, 2010; Wright & Ashford, 1998). This standard was "intended to determine the effects of freezing and thawing on units conforming to the dimensional requirements of Specification C936/C936M while immersed in a test solution. Other types of segmental concrete paving units that do not conform to the dimensional requirements of Specification C936/C936M may be tested using this test method". Specification C936/C936M "is intended for interlocking concrete pavers used in the construction of paved surfaces and manufactured from cementitious materials, aggregates, chemical admixtures, and other constituents such as integral water repellents. The specification also offers guidelines for physical requirements, sampling and testing, visual inspection, and rejection of specimens".

For this test, six SRPs were electrically tested/baselined (i.e., LED functionality) and then placed in two separate 300-gallon tubs of water inside an ESPEC walk-in environmental chamber. The first tub contained three SRPs in fresh water, to assess moisture conditioning capabilities, and the second tub contained three SRPs in a saltwater solution (i.e., ~ 3 % by weight NaCl) to assess performance in an expected real-world corrosive environment. The test consisted of 10 cycles where the ESPEC chamber temperature was set to -20 ℃ for 48 hours and then increased to 50 ℃ for 48 hours. This approximate five-day period constituted one test cycle. At the end of each test cycle, the SRPs were removed from the water tanks, dried with a lint-free towel, weighed, inspected for breaches in the physical structure, and then electrically tested. The apparatus for weighing the pavers was constructed from wood and the following steps were followed to mitigate any negative effects: 1) the fixture was stored in the temperature-controlled Engineering Materials and Structural Testing Laboratory (EMSTL) at Marquette University (MU), 2) for every measurement the pavers were dried with a lint-free cloth prior to being placed on the test jig, and 3) the scale was tared with the fixture weight prior to the pavers being placed on the jig and weighed. Once electrical testing was complete, the pavers were placed back into the water tanks to begin the next test cycle. These cycles were repeated for 10 iterations. The test articles (i.e., six SRPs) were simultaneously tested during the entire test period in ESPEC environmental chamber shown in Figure 4.

Figure 4. Walk-in Sized, ESPEC Temperature and Humidity-Controlled Room for Freeze/Thaw and Moisture Conditioning Testing

3.3 Heavy Vehicle Simulation (HVS)

The Heavy Vehicle Simulation (HVS) test was conducted to investigate the mechanical properties and evaluate LED operation of the SRPs. The testing was performed in accordance with recognized industry standard practices for paved surfaces. Testing was performed on the MU campus in the SR Pilot Project area located on the south side of Engineering Hall as shown in Figure 5. Limited electrical testing was accomplished to verify paver operation before and during HVS testing and consisted of verifying LED operation.

Figure 5. Heavy Vehicle Simulation (HVS) Test Facility Located at Marquette University

Heavy vehicle traffic is a contributing factor to roadway material failures. As mentioned before the SRPs consist of laminate material sandwiched between two glass layers. Since the glass and laminate materials clearly have different material compression coefficients, continuously cycling the pavers with a loaded wheel allows SRP mechanical and electrical functionality be evaluated in real-world conditions.

HVS testing was planned based on a load of 40kN (9,000 lbs.) super single test wheel load making one million, bi-directional passes at slow speeds of 1.3-2.2 m/s (3-5 mph) along the centerline of the SRPs (i.e., without wheel wander). This test regime was intended to evaluate system performance under extreme loading conditions (i.e., heavy wheel loads traveling at slow speeds). Testing was accomplished with the SRP grid installed on the surface of a doweled, Jointed Plain Concrete Pavement (JPCP) composed of a 10-inch concrete slab over a 6” crushed aggregate base layer over a silty-clay subgrade. The HVS test rig was earth grounded, via the side rails, to avoid static electricity concerns associated with the dry winter season.

The actual HVS testing used a 42.22 kN (9,500 lb) wheel load moving at approximately 0.57 m/s (1.3 MPH). The relative damage induced by these loading variables can be analyzed following the Equivalent Single Axle Loading (ESAL) concept developed by the American Association of State Highway Transportation Officials (AASHTO). The 42.22 kN single wheel load can be considered to be approximately 1.241 times more damaging than the 40 kN wheel load based on the 4th power approximation for equivalent loadings, (i.e., (42.22/40)^4 = 1.24 ESALs). Furthermore, allowable ESALs on concrete pavements are inversely related to the static modulus of sub grade reaction k-value. The plate-load test was originally used for determining static subgrade k-values; however, present analysis methods commonly back-calculate subgrade k-values using center-slab surface deflections produced by a Falling Weight Deflectometer (FWD), which produces deflections that simulate wheel loads moving at highways speeds. The FWD deflection-based back-calculated subgrade k-value is typically considered as the dynamic k-value, which is commonly assumed to be approximately twice that of the static k-value. When used in the context of the AASHTO concrete pavement design, converting from wheel loads traveling at highway speeds to creep speeds may be simulated by a 50% reduction in the design subgrade k-value. Comparing allowable ESAls over a range of design subgrade k-values yields a speed related damage factor of approximately 1.25, i.e., the slowly moving wheel loads are approximately 1.25 times more damaging that loads traveling at highway speeds. Combining the noted load and speed effects, each pass of the HVS can be equated to approximately 1.55 ESALs (i.e., 1.24*1.25 = 1.551).

4. Test Results

4.1 Moisture Conditioning Duration

The testing was conducted between 17 July 2017 and 29 August 2017 and the moisture conditioning duration testing resulted in essentially no measurable weight gain using a 100lb load cell with 0.02lb resolution. In one instance (S/N 3A), the post-submergence weight increased by 0.02lb after the one-week test period, but the paver’s weight returned to its original baseline value after the next submergence period. Based on this result, a second two-week test period was accomplished resulting in a consistent 0.04lb weight increase in each of the three test articles.

In all but one case, the LEDs were operational pre and post testing for each moisture duration test period. After the second two-week submergence test, paver S/N 3A failed electrical testing. Since the failure could not be attributed directly to increase moisture content, SR conducted an in-depth investigation (including photovoltaic testing using the apparatus shown in Figure 8) and determined that a corroded wire (Figure 6) was the root cause of the observed failure. The wire was exposed, due to a wire shielding flaw during manufacturing (Figure 7) and acted like a wick during the moisture duration tests. Improved manufacturing processes and use of more robust components will prevent similar future failures.

Figure 6. Photograph Revealing Cord Damage on Panel S/N 3A

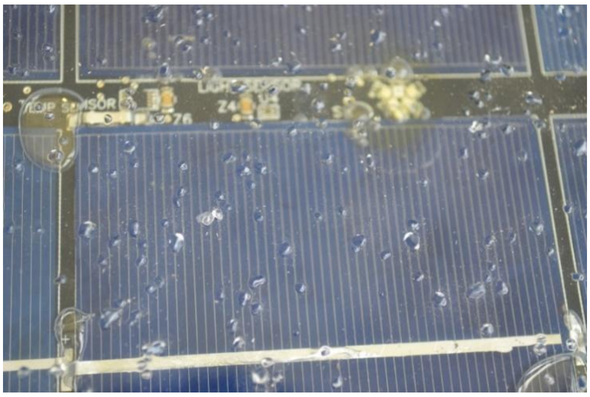

Figure 7. Example Panel Variations due to Manufacturing. Process (i.e., Internal in-Polymer "Bubble" Formation

The wires were cleaned/repaired and then LED functionality and photovoltaic tests were conducted on all three panels at the SR facility. Figure 8 shows the underside of the SR solar tester. It contains seven 500W lamps for a total of 3500W. The entire apparatus was placed on top of a single Solar Roadway panel during testing and the results are provided in Table 1.

Figure 8. Photograph of the Solar Roadway Panel Solar Tester

Table 1. Solar Data Collected at the SR Facility

Panel	Volts	Amps	Power
3A	22.03	1.21	26.7 watts
3B	21.51	1.14	24.5 watts
3C	21.59	1.18	25.5 watts

The Table 1 results are typical values for SRPs.

The moisture conditioning testing resulted in essentially no measurable weight gain using a 100lb load cell with 0.02lb resolution. The SRPs tested in the EMSTL at MU campus met or exceeded the moisture conditioning duration test standards described in ASTM D570-98(2010) e1.

4.2 Freeze/Thaw Cycling

Freeze/Thaw testing was conducted between 23 February 2018 and 20 April 2018 on six “SR3” solar pavers with S/N’s 1A-1F. For all specimens, there was no gain in paver mass detectable to the nearest 0.02 lb. In addition, no physical defects were noted after the 10 freeze/thaw cycles.

Finally, in all cases, the LEDs were operational in pre and post testing of each of the Freeze/Thaw test cycles. The six SRPs tested showed no sign of any adverse effect after rigorous Freeze/Thaw testing. The pavers neither gained any mass due to water infiltration nor showed any sign of physical distress after the test regimen.

4.3 Heavy Vehicle Simulation (HVS)

HVS testing on six SRPs with S/N’s 015A-015F began on 9 July 2018 and ended on September 30. The HVS fixture accumulated 637,948 actual load passes, or approximately 989,457 ESAL cycles (i.e., 637,948*1.55 = 989,457). There was no physical damage was to the SRP during HVS testing.

The LEDs in all six pavers were operational prior to HVS testing. During HVS testing, however, LED functionality steadily degraded. At the end of the test, the LEDs in pavers 015A and 015E were not operational. LEDs on pavers 015B and 0015C were functional but degraded to a random pattern within approximately two hours of paver power or color reset. Approximately one-third of the LEDs in pavers 015D and 015F remained operational. LED status is depicted on Figure 9.

Figure 9. Light Emitting Diode Status a) on 9 July 2018 (S/N's 015A-015F Depicted from Front to Back) and b) on 18 September 2018 (S/N's 015A-015F Depicted from Left to Right)

The observed LED performance variations were again attributed to variations in the SRP prototype's manufacturing process, previously shown in Figure 5 (i.e., cracked internal PV cells, internal in-polymer "bubble" formations, variances in the external "etched" surface grip/traction features, etc.), and wire corrosion due to ingress from cracked wire shields during continuous outdoor operation.

5. Conclusions

Three different tests were conducted to evaluate the mechanical properties of SRPs. The results show the current SRPs to be robust, resilient, and functional when subject to "real-world" test conditions. None of the observed anomalies were catastrophic failures and all were related to variations due to the manufacturing process. Finally, no direct comparison to concrete, asphalt, or other plastic materials can be made due to the unique nature of the SRPs and the materials used in their manufacture.

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