Final Report

Wind Uplift of Green Roof Systems

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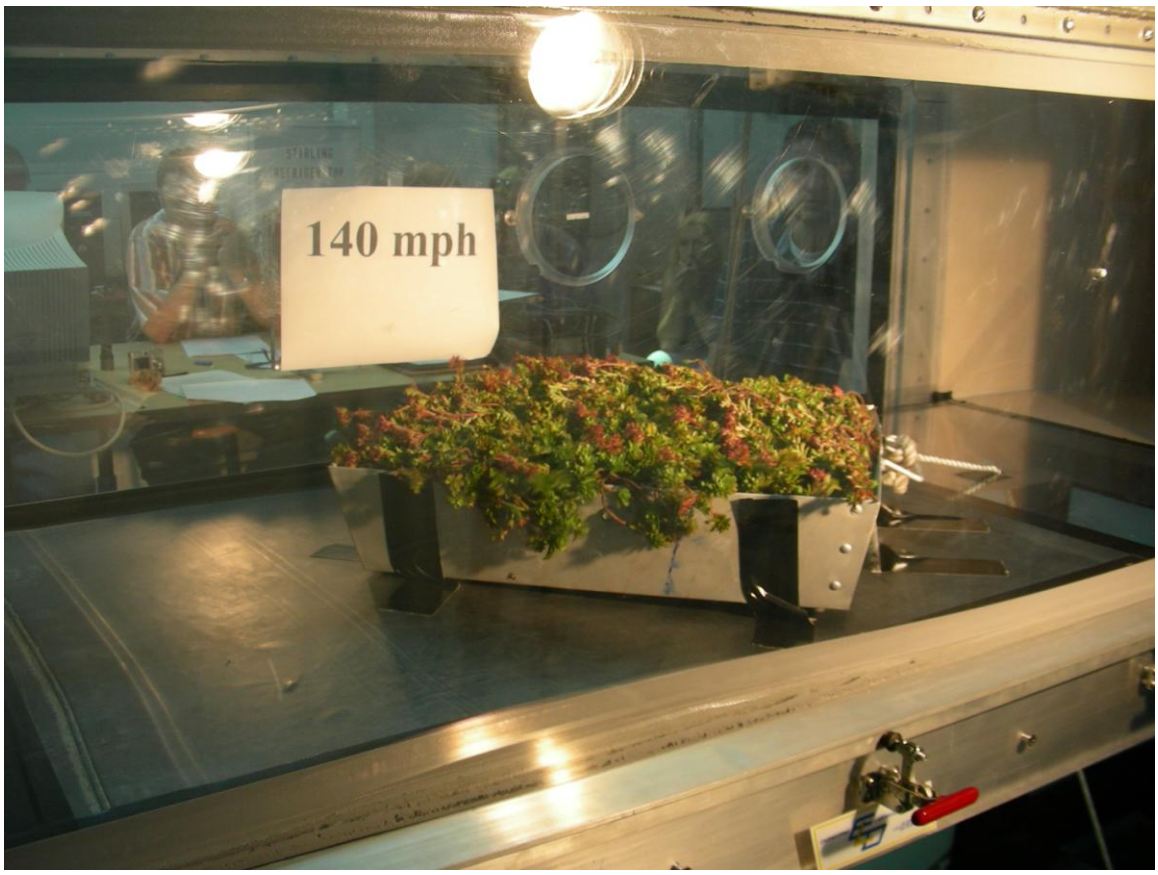
Southern Illinois University Edwardsville
Dr. Bill Retzlaff
Dr. Serdar Celik
Dr. Susan Morgan

Green Roof Blocks
Mr. Kelly Luckett

National Roofing Contractors Association
Mr. Mark Graham



Wind uplift of green roof components and systems has been a topic of considerable debate recently. There are ongoing efforts to develop a wind "standard" and design guidelines for green roof systems. However, besides some anecdotal evidence in the United States of a few green roofs that have "survived" significant wind events, little scientific testing has been presented or published that would steer development of standards or guidelines. This final report, Wind Uplift of Green Roof Systems, describes an initial systematic evaluation of wind uplift of green roof components in a recirculating wind tunnel located at Southern Illinois University Edwardsville (SIUE). The intent was to subject green roof components to a variety of wind uplift conditions and to address three primary hypotheses in order to provide guidance for standard development and further product testing and evaluation.

Project Description

This research project evaluated wind uplift of green roof systems using a recirculating wind tunnel available in the Mechanical Engineering Department at SIUE.

The project had three primary research hypotheses:

Hypothesis #1 – Four inches of fully vegetated growth media can sustain two minute wind gusts greater than 90 MPH.

Hypothesis #2 – There is a minimum level of vegetation required to bind the growth media in order to resist scour during two minute wind gusts greater than 90 MPH. Identify that level.

Hypothesis #3 – There are surface treatments that are effective in minimizing scour at various wind speeds. Identify the treatment and the wind speed at which it is no longer effective.

Materials and Methods

Working in concert with Mr. Mark Graham (Associate Executive Director, Technical Services, NRCA) and Mr. Kelly Luckett (President, Green Roof Blocks) the team at SIUE (Drs. Celik, Morgan, and Retzlaff) designed a series of wind tunnel experiments to evaluate the three hypotheses as listed above. Testing was conducted on Saturday June 13, 2009 (Test Day One) and Sunday August 9, 2009 (Test Day Two).

<u>Preparation of the Wind Tunnel:</u>
In order to alleviate concerns regarding possible debris entering the wind tunnel intake system, various means of filtration were explored. Porosity and location of the filtration material might affect the fan's ability to obtain the RPMs necessary to reach the required wind speed to conduct relevant uplift testing of green roof systems. Through trial and error, aluminum window screen located approximately 8 feet from the downstream end of the testing chamber proved to be effective in containing particulate while allowing adequate airflow required for the fan to reach the RPMs necessary to generate wind speeds exceeding 140 mph.

Another concern regarding the safeguarding of the wind tunnel apparatus was possible damage to the interior surface of the testing chamber and the system air duct caused by contact of dislodged green roof modules or other green roof materials. To minimize this concern the green roof systems tested (anodized aluminum trays and fabric modules) were tethered throughout testing to prevent the green roof modules from moving beyond the test chamber. In addition, plexi-glass was used to protect the testing chamber throughout the testing procedures. The initial installation of the plexi-glass material was achieved by using high quality duct tape at the perimeter of the plexi-glass sheeting. The sheeting used to protect the floor of the testing chamber bowed upward during initial test runs that achieved wind speeds exceeding 75 mph. Subsequent testing with a fully vegetated green roof module resulted in the slight movement of the module at wind speeds of 107 mph. The plexi-glass covering the floor of the testing chamber was then bolted to the floor of the testing chamber. Additionally, a layer of standard EPDM roofing membrane was adhered to the protective plexi-glass sheeting to more accurately represent the installation of the green roof module on a roofing membrane rather than resting on the surface of the plexi-glass.

Note that the wind tunnel was also evaluated as an open system (see Appendix 1). However, appropriate wind speeds were not achieved so the wind tunnel was operated (as below) in the recirculating mode).

Wind Tunnel Specifications:

The Aerodynamics & Energy Laboratory in the School of Engineering at Southern Illinois University Edwardsville houses a subsonic, recirculating wind tunnel manufactured by Engineering Laboratory Design Inc. The custom designed wind tunnel is used for both research and education purposes. It operates as a closed loop with a two-stage axial flow fan driven by a 300 hp electric motor. The air temperature is controlled by a heat exchanger located before the test section which provides a stable and high quality air flow for research activities. Below are the specifications of the wind tunnel:

- Test section dimensions: L x W x H = 72.0 in. x 30.0 in. x 24.0 in.
- Air temperature range: 60-70 °F (can be extended by additional heaters and coolers)
- Air velocity range: 10-300 fps (6.8 - 204.5 mph)
- Fan: Two-stage axial flow fan (300 hp)
- Turbulence intensity: <0.25%
- Fiberglass ducts
- Moveable ceiling
- 2-axis positioning system
- Acoustic enclosure

The calibration for the velocity measurements were made by the manufacturer using a TSI IFA 300 Constant Temperature Anemometer System employing a Model 1210-20 single film-sensor probe and a Model 1210-T1.5 single wire-sensor probe. Both probes were calibrated in the wind tunnel with a pitot-static probe against an MKS Model 398HD-00100 Baratron Pressure Transducer over a velocity range from 0 to 90 m/s. The calibration analysis showed that the

velocity is within ±1% of the centerline velocity except in the wall region (~1 in. from all walls). Turbulence intensity, which is the ratio of the root-mean-square (RMS) of turbulent velocity fluctuations to mean flow velocity, was measured as well. The highest turbulence intensity was observed to be 0.22% at the highest velocity.

Measurements and Calibration:

The measurements were obtained for the test samples in the test section. For realistic testing, an EPDM roofing membrane was adhered over the bottom panel of the test section. All green roof systems tested were placed on top of the EPDM membrane – simulating roofing conditions.

Regarding the test conditions of ASCE 7–Method 3 (Wind tunnel procedure), the effects of Reynolds number were minimized using smooth walls in the test section which results in decreased edge effects. The hydraulic diameter of the test section was considered to be adequate for only one green roof block in the test section.

The wind speeds for each test were obtained by using a high accuracy pitot tube and performing the theory of pitot tubes. Pitot tubes operate based on the Bernoulli Equation that applies to incompressible frictionless flow. The Bernoulli Equation is:

$$\frac{P_1}{\rho}+\frac{V_1^2}{2}+gz_1=\frac{P_2}{\rho}+\frac{V_2^2}{2}+gz_2 \quad (1)$$

When Location 2 is where stagnation of the air occurs and Location 1 is in the free stream area, the Bernoulli Equation is modified to solve for the free stream velocity as shown in Equation 2:

$$V_1=\sqrt{\frac{2(P_2-P_1)}{\rho}} \quad (2)$$

Hence for varying pressure differences, corresponding free stream velocities were tabulated using Equation 2 in Excel. The pitot tube in the test section was placed at the center from the side walls (x = 15 in.), 4 inches below the upper wall (z = -4 in. equal in magnitude to the height of the tested blocks), and leveled with the test samples in the y-direction (y = 0 in.).

The fan shaft RPM is controlled by a transistor invertor type variable frequency controller (VFC). To increase the wind speed, a frequency value ranging from 0 to 60Hz with increments of 0.1 Hz was set on the digital screen. Finally a correlation between input frequency and wind speed was achieved. Table 1 shows the frequency, pressure difference, and wind speeds achieved for the reported tests.

A linear relationship between the input frequency and wind speed was obtained using a curve fitting technique. The equation below yielded a coefficient of determination (R^2) of 0.9999.

$$V=(3.3607*f)-3.2875 \quad (3)$$

where the velocity and frequency have the units mph and Hz, respectively.

Table 1. Tabulated values for frequency, dP, and velocity (m/s and mph) for the recirculating wind tunnel at SIUE.

f (Hz)	dP (in.H_20)	V (m/s)	V (mph)
5	0.1	6.36	14.24
10	0.44	13.35	29.86
15	1.1	21.11	47.22
20	2	28.46	63.67
25	3.2	36.00	80.54
30	4.65	43.40	97.08
35	6.45	51.11	114.34
40	8.5	58.68	131.26
43	9.9	63.32	141.66

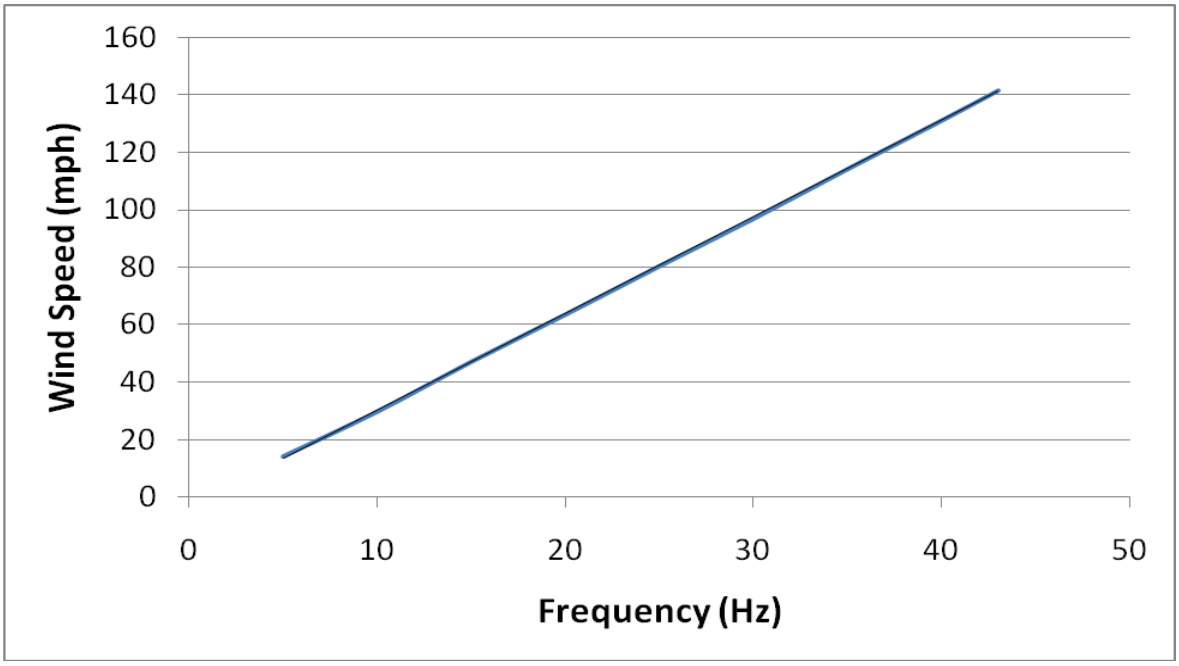


Figure 1. Frequency vs. wind speed values for the recirculating wind tunnel at SIUE.

General Testing Procedures:

Test for Hypothesis #1 –included placing fully vegetated green roof systems in the wind tunnel and subjecting them to assigned wind speeds and noting displacement and outcomes.

Test for Hypothesis #2 –included placing partially vegetated (with percentage of roof coverage quantified) green roof systems in the wind tunnel and subjecting them to assigned wind speeds and noting displacement and outcomes.

Test for Hypothesis #3 – involved placing un-vegetated green roof systems with various surface treatments in the wind tunnel and subjecting them to assigned wind speeds and noting displacement and outcomes.

In all three tests above, we precisely controlled wind speed and monitored displacement by personal observation and also by camera. (The plexi-glass chamber in the wind tunnel provided 360 degree viewing of testing materials.) Weight loss of the green roof modules were also determined by weighing each module prior to and immediately following each wind tunnel test. In addition, we collected any materials at the end of the wind tunnel in front of the debris screen that were displaced during testing and weighed them to evaluate loss of materials (plant, growth media, etc.) from each green roof system tested. Percentage of vegetative coverage of a green roof system was determined when needed by a circle-dot grid (Forrester 2007) before placement in the wind tunnel.

Testing was conducted at the following wind speeds and duration: 60 mph (1 min); 75 mph (1 min); 90 mph (2 min); 105 mph (3 min); 120 mph (5 min); and 140 mph (5 min).

Point of failure is defined in these wind tunnel tests as one of the following: displacement of the green roof module, displacement of the vegetation (more than shedding a few leaves), and displacement of the growth media (more than scouring minimal media).

Testing on day #1 was designed to evaluate as many of the conditions as possible to address all three proposed hypotheses and to direct future wind tunnel work (on additional testing dates). Following testing on day #1, the team decided to follow-up the first tests with wind tunnel testing designed to further answer the proposed hypothesis (testing day #2).

On testing day #2, in order to attempt to satisfy hypothesis #2, eight (18 inch x 18 inch) four-inch deep aluminum modules were pre-grown at a local greenhouse facility (Jost Greenhouses) to varying levels of vegetative coverage. Prior to testing, each module was evaluated to determine the size of the largest area in the surface of the module that was not covered by vegetation. Four of these modules were tested at the wind speeds and durations used on test day #1 to identify the failure point at which a significant amount of growth media is displaced from the module.

In order to attempt to satisfy hypothesis #3, three strategies for controlling wind scour during the green roof plant establishment period were evaluated. These included liquid binding agents, fabric modules, and erosion control blankets.

Liquid binding agents

Seven (18 inch x 18 inch) four-inch deep aluminum modules were filled with growth media. The media chosen was expanded clay based (80% Arkalyte: 20% composted pine bark – see Appendix for growth media specifications) because the clay is among the lightest aggregates used for green roof growth media. The growth media had been stored indoors for over one year prior to the testing, thus serving to minimize the water content and therefore allow testing of a "worst case" scenario. Two commercially available soil binding agents were procured prior to this testing date (Liquid Binding Agent A and Liquid Binding Agent T). Each binding agent was applied to two modules containing growth media only. One of the binding agents has been previously utilized in a green roof application. This binding agent was also applied to one module with newly planted sedum plugs, one module with newly applied sedum cuttings, and one module with a combination of sedum plugs and cuttings. (These modules were from the pool identified above.) Though the research team accepted the products provided by two different manufacturers and as a matter of courtesy, tested both products, the role of the testing conducted by the research team was not to test the effectiveness of one product over that of another. The role of the current testing is to evaluate the principle of utilizing a surface treatment as an effective means of controlling wind scour on a newly planted green roof. The effectiveness of one product over another speaks to the suitability of a particular product or formulation and not to the viability of the principle of utilizing a chemical surface treatment to control wind scour in newly planted green roofs. It is incumbent upon manufacturers wishing to market products for this purpose to conduct the necessary research and development to determine proper formulation, mixing, and application of these products.

Fabric Modules

Two fabric modules (unplanted – no vegetative coverage) were also tested nested against one another and employing a wind deflector plate to conclude the testing for module displacement. Following this test, Sedum plugs were inserted through openings made in the top surface of the fabric modules and the test was repeated.

Erosion Control Blankets

In separate tests, two aluminum modules filled with growth media only were covered with two different erosion control "blankets" - netting and burlap - to evaluate the potential for reducing wind uplift of growth media.

Results

Testing Day One – June 13, 2009

Weather Conditions: Partly cloudy, low temperature 61 degrees – high temperature 83 degrees

Green roof modules (anodized aluminum trays and fabric modules) that were tested on Day 1 had been located outdoors prior to testing. The St. Louis area received no rain during the 48 hours prior to testing.

Wind Tunnel Day One Test #1 (green roof model with 100% vegetative coverage)

Test Setup:

A (24 inch x 24 inch) four-inch deep aluminum green roof module with 100% vegetative coverage ('Weihenstephaner Gold') was placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. The green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

The green roof module in this test (#1) remained stable through five minutes at a wind speed of 120 mph. The green roof module in this test began to slide during the increase from 120 mph to

Table 2. Wind tunnel conditions and results during Test #1 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	5	achieved
140	--	module began sliding before this wind speed was achieved
[1]Module Weight prior to test (lbs):		66.26
[1]Module Weight following test (lbs):		65.50
[2]Total Module Weight loss following test (lbs):		0.76
[3]Calculated weight of collected materials (gms):		18.36

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

the next wind speed, thus marking the failure point at speeds above 120 mph. The aluminum module used in this test was tapered such that empty modules of this type can be nested inside one another; allowing stacking (similar to paper cups). As such, horizontal wind forces can be directed downward by the angled sides of the aluminum green roof module. Furthermore, the green roof module rests on 3 inch x 3 inch x 3/8 inch rubber pads at the corners and the center of the module. Therefore, wind directed down the perpendicular side of the aluminum module may have been forced under the module via the 3/8 inch space between the EPDM roof membrane surface and the bottom of the green roof module, providing uplift.

Wind Tunnel Day One Test #2 (green roof model from Test #1 with 100% vegetative coverage AND a wind deflector located on the leading edge of the green roof model)

Test Setup:

A (24 inch x 24 inch) four-inch deep aluminum green roof module with 100% vegetative coverage ('Weihenstephaner Gold') was re-placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. A "wind deflector" was placed in front of the leading edge of the green roof module to prevent wind from passing underneath the module during this test. The green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

The green roof module in this test (#2) remained stable through five minutes at a wind speed of

Table 3. Wind tunnel conditions and results during Test #2 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	5	achieved
140	5	achieved
[1]Module Weight prior to test (lbs):		66.26
[1]Module Weight following test (lbs):		65.50
[2]Total Module Weight loss following test (lbs):		0.76
[3]Calculated weight of collected materials (gms):		18.36

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

140 mph. Note in this test (#2) that the initial and final weights were reported as the same as those for test #1 – the team did not re-weigh the module between these two tests as we were evaluating whether we could prevent module movement in test #2 as opposed to module failure (test #1).

During test #1 and #2, the team determined that the size of the green roof modules (24 inches x 24 inches) was detrimental in that turbulence along the sides of the wind tunnel chamber was observed. Loose materials were moving upstream – a common issue in wind tunnel chambers if tested materials are "large". Thus, in subsequent wind tunnel tests (on day one and following dates) using anodized aluminum trays, the testing module size was reduced to 18 inches x 18 inches to reduce turbulence in the wind tunnel chamber. In addition, a roofing consultant provided by the NRCA who was present on testing day one informed the team that corners of any roofing system were subjected to significantly more wind stress. Therefore, modules in succeeding tests for media displacement were placed at a 45 degree angle to the wind direction (i.e., instead of being perpendicular, the corner faced into the wind) to provide maximum stress during the wind tunnel test.

Wind Tunnel Day One Test #3 (18 inch x 18 inch green roof model with 100% vegetative coverage)

Test Setup:

A (24 inch x 24 inch) four-inch deep aluminum green roof module was modified by "refabricating" the larger module into an 18 inch x 18 inch green roof module. Mature vegetation with 100% vegetative coverage ('Weihenstephaner Gold') was transplanted into this smaller module from the larger module (an 18 inch by 18 inch plug was cut from a 24 inch x 24 inch module and transplanted into the 18 inch x 18 inch module). The newly prepared 18 inch x 18 inch module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The rope tether in this test was tight (no slack) so that there would be no module displacement and the team could evaluate growth media or plant material displacement. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

The plant material and growth media (at 100% vegetative coverage and newly placed in the fabricated module) remained stable and secure in the 18 inch x 18 inch aluminum module for 5 minutes at 140 mph.

Table 4. Wind tunnel conditions and results during Test #3 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	5	achieved
140	5	achieved
[1]Module Weight prior to test (lbs):		36.28
[1]Module Weight following test (lbs):		35.83
[2]Total Module Weight loss following test (lbs):		0.45
[3]Calculated weight of collected materials (gms):		11.65

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day One Test #4 (green roof model with approximately 71% vegetative coverage)

Test Setup:

A (24 inch x 24 inch) four-inch deep aluminum green roof module with approximately 71% vegetative coverage (initially planted with mixed Sedum plugs and supplemented with cuttings recently) was placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. As before, a "wind deflector" was placed in front of the leading edge of the green roof module to prevent wind from passing underneath the module during this test. The green roof module was tethered tightly with a rope to ensure that the module would not be displaced during testing. Vegetative roof coverage was determined using a circle dot-grid as described in Forrester (2007).

Additional Observations:

Green roof growth media exposed (not covered by plant materials) was uplifted (scoured) as wind speeds were increased above 75 mph.

Table 5. Wind tunnel conditions and results during Test #4 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	--	Aggregate displacement – test stopped
105	--	not tested
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		72.85
[1]Module Weight following test (lbs):		72.46
[2]Total Module Weight loss following test (lbs):		0.39
[3]Calculated weight of collected materials (gms):		68.92

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day One Test #5 (18 inch x 18 inch green roof model with NO vegetative coverage)

Test Setup:

The vegetation and growth media "plug" in the modified 18 inch x 18 inch green roof module used in Test #3 was removed and replaced with a green roof growth media blend that had been stored on the rooftop and exposed to weather. This growth media mixture was comprised of 80% Haydite (3/8 inch aggregate) and 20% composted pine bark. The 18 inch x 18 inch module containing growth media only (no vegetation) was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

Large aggregate pieces of the growth media were displaced at 30 mph – this test was ended before reaching target wind speeds.

Table 6. Wind tunnel conditions and results during Test #5 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	--	not achieved – shut down @ 30 mph
75	--	not tested
90	--	not tested
105	--	not tested
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		32.83
[1]Module Weight following test (lbs):		32.49
[2]Total Module Weight loss following test (lbs):		0.34
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day One Test #6 (green roof fabric model with 100% vegetative coverage)

Test Setup:

A (20 inch x 32 inch) five-inch deep fabric green roof module with 100% vegetative coverage (mixed Sedum species) was placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. The green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

The green roof (fabric) module in this Test (#6) remained stable through one minute at a wind speed of 75 mph. The green roof (fabric) module in this test began to slide (at approximately 84 mph as determined by the f (Hz) at the time of sliding) during the increase from 75 mph to the next wind speed, thus marking the failure point at speeds above 75 mph. The green roof fabric module is large and has a very large canopy (almost filling the width of the wind tunnel chamber).

Table 7. Wind tunnel conditions and results during Test #6 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	--	Module sliding prior to achieving target speed
105	--	not tested
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		89.38
[1]Module Weight following test (lbs):		88.52
[2]Total Module Weight loss following test (lbs):		0.86
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day One Test #7 (green roof fabric model with 100% vegetative coverage)

Test Setup:

Two (20 inch x 32 inch) five-inch deep fabric green roof module with 100% vegetative coverage (mixed Sedum species) were placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. The downwind green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

Two fabric modules with 100% vegetative coverage nested against one another provided significantly more resistance to sliding under horizontal wind forces than a single fabric module. After two minutes at a wind speed of 130 MPH the leading fabric module lifted from the EPDM surface concluding the test and marking the failure point at 130 MPH.

Table 8. Wind tunnel conditions and results during Test #7 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	5	achieved
130	--	After 2 minutes – lifting of leading edge of fabric module
140	--	not tested
[1]Module Weight prior to test (lbs):		89.38 pak 1; 82.57 pak 2
[1]Module Weight following test (lbs):		88.52 pak 1; 81.49 pak 2
[2]Total Module Weight loss following test (lbs):		0.86 pak 1; 1.08 pak 2
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day One Test #8 (green roof fabric model with 100% vegetative coverage AND a wind deflector located on the leading edge of the green roof model)

Test Setup:

One (20 inch x 32 inch) five-inch deep fabric green roof module with 100% vegetative coverage (mixed Sedum species) was placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. A "wind deflector" was placed in front of the leading edge of the green roof module to prevent wind from passing underneath the module during this test. The green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

The green roof (fabric) module with the wind deflector in place in this Test (#8) remained stable through one minute at a wind speed of 120 mph. The green roof (fabric) module in this test began to slide during the increase from 120 mph to the next wind speed, thus marking the failure point at speeds above 120 mph.

Table 9. Wind tunnel conditions and results during Test #6 on 6/13/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	--	skipped
75	--	skipped
90	--	skipped
105	--	skipped
120	1	achieved
140	--	Module sliding prior to achieving target speed
[1]Module Weight prior to test (lbs):		82.57
[1]Module Weight following test (lbs):		81.49
[2]Total Module Weight loss following test (lbs):		1.08
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Results

Testing Day Two – August 9, 2009

Weather Conditions: Sunny, low temperature 76 degrees – high temperature 95 degrees

Green roof modules used during testing day #2 were planted June 19, 2009 and were cared for in a greenhouse (Jost Greenhouses) prior to testing. The partially-vegetated modules were evaluated to determine the diameter of the largest area not covered by vegetation. Four modules were selected, one containing a maximum diameter size bare space of 3", one with 4" bare space, one with 5" bare space, and one with 6" bare space. Testing was begun with the module containing the 4" diameter bare space – successful testing at the highest wind speed could eliminate the necessity to conduct testing on the module containing the 3" bare space.

Wind Tunnel Day Two Test #1 (18 inch x 18 inch green roof model with at least one maximum bare space of 4 inches in diameter)

Test Setup:

The (18 inch x 18 inch) four inch deep aluminum partially-vegetated green roof module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

In order to accurately determine the size of the openings (bare growth media between vegetated areas) in the vegetated area, a tracing on an acetate sheet of the openings was made before placing in the wind tunnel (copies of tracings in Appendix 2). Later these "opening" were cut out and the area (in percentage coverage) was determined for the tested module.

Additional Observations:

Growth media and vegetation remained stable through wind speeds of 75 mph. Minor scouring of the surface growth media occurred after wind speeds were increased to 90 mph. After initially losing some surface aggregate once 90 mph was reached, the remaining growth media and vegetation remained stable throughout the two minute duration at wind speeds of 90 mph. Scouring increased significantly upon the increase in wind speed to 105 miles per hour. Significant erosion of non-vegetated portions of the green roof continued throughout the three minute duration of wind speeds at 105 mph. Erosion created craters and gorges that continued to increase in depth and width throughout the 3-minute duration of wind speeds at 105 mph, constituting failure point and concluding the test.

Table 10. Wind tunnel conditions and results during Test #1 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	scouring of growth media – stopped after 3 minutes
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		37.18
[1]Module Weight following test (lbs):		35.68
[2]Total Module Weight loss following test (lbs):		1.5
[3]Calculated weight of collected materials (gms):		393.35
[4]% vegetated coverage		92%

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Note[4]. Tracings of "openings" were cut out, placed on a scanner, scanned, and the size (square inches) of the scanned segments was determined using SigmaScan Pro v5.0 (1999 SPSS) software. Percentage vegetated coverage = ((324 sq. in. – scanned sq. in.)/324 sq. in.) *100; where 324 sq. in. is the surface area of the 18 in. x 18 in. anodized aluminum module.

Wind Tunnel Day Two Test #2 (18 inch x 18 inch green roof model with at least one maximum bare space of 6 inches in diameter)

Test Setup:

The (18 inch x 18 inch) four-inch deep aluminum partially-vegetated green roof module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

In order to accurately determine the size of the openings (bare growth media between vegetated areas) in the vegetated area, a tracing on an acetate sheet of the openings was made before placing in the wind tunnel (copies of tracings in Appendix 2). Later these "openings" were cut out and the area (in percentage coverage) was determined for the tested module.

Additional Observations:

Growth media and vegetation remained stable through wind speeds of 60 mph. Minor scouring of the surface growth media occurred after wind speeds were increased to 75 mph, occasionally losing some surface aggregate throughout the one minute duration at this wind speed. Scouring increased significantly upon the increase in wind speed to 90 mph. Significant erosion of non-vegetated portions of the green roof continued throughout the two minute duration at this wind speed and the three minute duration of wind speeds at 105 mph. Erosion created craters and gorges that continued to increase in depth and width constituting the failure point and concluding the test.

Table 11. Wind tunnel conditions and results during Test #2 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved – scouring of growth media
90	2	achieved – scouring of growth media
105	3	achieved – scouring of growth media – stopped after 3 minutes
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		36.84
[1]Module Weight following test (lbs):		35.75
[2]Total Module Weight loss following test (lbs):		1.09
[3]Calculated weight of collected materials (gms):		289.16
[4]% vegetated coverage		88%

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Note[4]. Tracings of "openings" were cut out, placed on a scanner, scanned, and the size (square inches) of the scanned segments was determined using SigmaScan Pro v5.0 (1999 SPSS) softwareSigmaScan Pro v5.0 (1999 SPSS) software. Percentage vegetated coverage = ((324 sq. in. – scanned sq. in.)/324 sq. in.) *100; where 324 sq. in. is the surface area of the 18 in. x 18 in. anodized aluminum module.

Wind Tunnel Day Two Test #3 (18 inch x 18 inch green roof model with at least one maximum bare space of 5 inches in diameter)

Test Setup:

The (18 inch x 18 inch) four inch deep aluminum partially-vegetated green roof module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

In order to accurately determine the size of the openings (bare growth media between vegetated areas) in the vegetated area, a tracing on an acetate sheet of the opening was made before placing in the wind tunnel (copies of tracings in Appendix 2). Later these "openings" were cut out and the area (in percentage coverage) was determined for the tested module.

During this test, after achieving 90 mph for 2 minutes, the test was stopped, the module was weighed, and then replaced as above in the wind tunnel testing chamber and the wind speed was re-started at 105 mph.

Additional Observations:

The growth media and vegetation remained stable through wind speeds of 75 MPH. Minor scouring of the surface growth media occurred after wind speeds were increased to 90 mph, occasionally losing minimal surface aggregate throughout the two minute duration at this wind speed. The testing was stopped after the two minute duration at 90 mph, the module was weighed, and the displaced growth media and vegetation were collected and weighed. The difference in the post-testing module weight from the pre-testing module weight indicated displacement of 85.35 grams of growth media and plant material. The test then resumed at wind speeds of 105 MPH. Significant scouring began as the wind speeds approached 105 MPH and continued throughout the three minute duration at this wind speed. Erosion created craters and gorges that continued to increase in depth and width constituting the failure point and concluding the test.

Table 12. Wind tunnel conditions and results during Test #3 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved – scouring occurred – removed from chamber and weighed
105	3	restarted after weighing above – scouring of growth media – stopped after 3 minutes
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		37.73
[1]Module Weight following 90 mph (lbs):		37.31
[1]Module Weight following test (lbs):		36.25
[2]Total Module Weight loss following test (lbs):		1.48
[3]Calculated weight of collected materials after 90 mph (gms):		85.35
[3]Calculated weight of collected materials after 105 mph (gms):		329.98
[4]Total weight of collected materials at end of test (gms):		415.33
[5]% vegetated coverage		94%

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Note[4]. Total collected weight = weight collected after 90 mph + weight collected after 105 mph.

Note[5]. Tracings of "openings" were cut out, placed on a scanner, scanned, and the size (square inches) of the scanned segments was determined using SigmaScan Pro v5.0 (1999 SPSS) softwareSigmaScan Pro v5.0 (1999 SPSS) software. Percentage vegetated coverage = ((324 sq. in. – scanned sq. in.)/324 sq. in.) *100; where 324 sq. in. is the surface area of the 18 in. x 18 in. anodized aluminum module.

Wind Tunnel Day Two Test #4 (18 inch x 18 inch green roof model with only one bare space of 6 inches in diameter)

Test Setup:

The (18 inch x 18 inch) four inch deep aluminum partially-vegetated green roof module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

In order to accurately determine the size of the openings (bare growth media between vegetated areas) in the vegetated area, a tracing on an acetate sheet of the openings was

made before placing in the wind tunnel (copies of tracings in Appendix 2). Later these "opening" were cut out and the area (in percentage coverage) was determined for the tested module.

In this test, the original module had 100% vegetative coverage. Thus, vegetation was "clipped" to create an un-vegetated area with a diameter of 6 inches in the center of the 18 in x 18 inch green roof module.

Additional Observations:

Growth media and vegetation remained stable through wind speeds of 60 mph. Minor scouring of the surface growth media occurred after wind speeds were increased to 75 mph, occasionally losing some surface aggregate throughout the one minute duration at this wind speed. Scouring increased significantly upon the increase in wind speed to 90 mph. Significant erosion of non-vegetated portions of the green roof continued throughout the two minute duration at this wind speed and the three minute duration of wind speeds at 105 mph. Erosion created craters and gorges that continued to increase in depth and width constituting failure point and concluding the test.

Table 13. Wind tunnel conditions and results during Test #4 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved - scouring
90	2	achieved – scouring of growth media
105	3	achieved – scouring of growth media – stopped after 3 minutes
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		35.58
[1]Module Weight following test (lbs):		34.32
[2]Total Module Weight loss following test (lbs):		1.26
[3]Calculated weight of collected materials (gms):		323.13
[4]% vegetated coverage		91%

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Note[4]. Tracings of "openings" were cut out, placed on a scanner, scanned, and the size (square inches) of the scanned segments was determined using SigmaScan Pro v5.0 (1999 SPSS) softwareSigmaScan Pro v5.0 (1999 SPSS) software. Percentage vegetated coverage = ((324 sq. in. – scanned sq. in.)/324 sq. in.) *100; where 324 sq. in. is the surface area of the 18 in. x 18 in. anodized aluminum module.

Wind Tunnel Day Two Test #5 (18 inch x 18 inch green roof fully vegetated model propagated with cuttings 60 days previous to test)

Test Setup:

The (18 inch x 18 inch) four-inch deep aluminum fully-vegetated green roof module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

The plant material and growth media remained stable in the module through five minutes at wind speeds of 120 mph. Some minor scouring of surface aggregate occurred at wind speeds of 140 mph. Interestingly, the effect of the wind force appeared as the vegetation parted in the form of the signature vortex "V" clearly visible during the test from an overhead vantage point. The wind tunnel fan began to approach the maximum operating temperature during the 140 mph testing period, so the test was concluded after only two minutes.

Table 14. Wind tunnel conditions and results during Test #5 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	5	achieved
140	2	wind tunnel heating up – some scour observed – testing stopped at 2 minutes
[1]Module Weight prior to test (lbs):		36.68
[1]Module Weight following test (lbs):		35.56
[2]Total Module Weight loss following test (lbs):		1.12
[3]Calculated weight of collected materials (gms):		149.41
[4]% vegetated coverage		100%

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Note[4]. Tracings of "openings" were cut out, placed on a scanner, scanned, and the size (square inches) of the scanned segments was determined using SigmaScan Pro v5.0 (1999 SPSS) softwareSigmaScan Pro v5.0 (1999 SPSS) software. Percentage vegetated coverage = ((324 sq. in. – scanned sq. in.)/324 sq. in.) *100; where 324 sq. in. is the surface area of the 18 in. x 18 in. anodized aluminum module.

Wind Tunnel Day Two Test #6 (18 inch x 18 inch green roof model with at least one maximum bare space of 3 inches in diameter)

Test Setup:

The (18 inch x 18 inch) four-inch deep aluminum partially-vegetated green roof module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

In order to accurately determine the size of the openings (bare growth media between vegetated areas) in the vegetated area, a tracing on an acetate sheet of the openings was made before placing in the wind tunnel (copies of tracings in Appendix 2). Later these "opening" were cut out and the area (in percentage coverage) was determined for the tested module.

Additional Observations:

Growth media and vegetation remained stable through wind speeds of 75 mph. Initially, some minor scouring of the surface growth media occurred after wind speeds were increased to 90 mph, but scouring seemed to taper off once wind speed reached 90 mph. Upon the increase to 105 mph, catastrophic loss of growth media occurred at the leading corner of the module and at the 3" in diameter non-vegetated areas. Growth media scour seemed to once again stabilize once wind speed reached 105 mph. Vegetation and growth media remained stable for the balance of the three minute duration at this wind speed, only occasionally losing growth media or plant particles. Scouring increased significantly upon the increase in wind speed from 105 mph to 120 mph. Again, scouring tapered off after the initial increase in wind speed to an occasional loss of growth media or plant particles. Due to the volume of displaced growth media and plant particles that had accumulated on the protective screening stretched across the exhaust end of the wind tunnel, airflow through the wind tunnel testing chamber was restricted, limiting the generation of additional wind speed. The testing was stopped after several minutes as wind speeds were unable to reach 120 mph.

Table 15. Wind tunnel conditions and results during Test #6 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved - scouring
105	3	achieved - scouring
120	--	unable to achieve wind speed
140	--	not tested
[1]Module Weight prior to test (lbs):		37.31
[1]Module Weight following test (lbs):		35.27
[2]Total Module Weight loss following test (lbs):		2.04
[3]Calculated weight of collected materials (gms):		523.42
[4]% vegetated coverage		95%

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Note[4]. Tracings of "openings" were cut out, placed on a scanner, scanned, and the size (square inches) of the scanned segments was determined using SigmaScan Pro v5.0 (1999 SPSS) softwareSigmaScan Pro v5.0 (1999 SPSS) software. Percentage vegetated coverage = ((324 sq. in. – scanned sq. in.)/324 sq. in.) *100; where 324 sq. in. is the surface area of the 18 in. x 18 in. anodized aluminum module.

Wind Tunnel Day Two Test #7 (18 inch x 18 inch green roof model with NO vegetative coverage – treated with Liquid Binding Agent A)

Test Setup:

An 18 inch x 18 inch green roof module containing an un-vegetated growth media mixture comprised of 80% Arkalyte (3/8 inch aggregate) and 20% composted pine bark was treated with a liquid binding agent (Liquid Binding Agent A 1:1 chemical:water) 48 hours prior to wind tunnel testing. This "treated" module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

Only 4 pieces of aggregate were observed in front of the screen in the wind tunnel.

Table 16. Wind tunnel conditions and results during Test #7 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	--	skipped
120	2	achieved
140	5	achieved
[1]Module Weight prior to test (lbs):		38.26
[1]Module Weight following test (lbs):		37.00
[2]Total Module Weight loss following test (lbs):		0.46
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day Two Test #8 (18 inch x 18 inch green roof model with NO vegetative coverage – treated with Liquid Binding Agent T)

Test Setup:

An 18 inch x 18 inch green roof module containing an un-vegetated growth media mixture comprised of 80% Arkalyte (3/8 inch aggregate) and 20% composted pine bark was treated with a liquid binding agent (Liquid Binding Agent T 1:2 chemical:water) 48 hours prior to wind tunnel testing. This "treated" module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

The same as with day two test #7, all previous tests identified the need for surface treatments to control wind scour of green roof growth media for green roofs with even the smallest size non-vegetated areas begins at wind speeds approaching 90 mph, the research team decided to begin test #8 at a wind speed of 90 mph. Since the next significant category of wind speed in wind load design is 120 mph, the research team decided to skip testing at the 105 mph wind speed, jumping from 90 mph directly to 120 mph. The surface if the growth media in test #8 experienced catastrophic displacement at the jump from 90 mph to 120 mph.

Table 17. Wind tunnel conditions and results during Test #8 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	--	skipped
75	--	skipped
90	2	achieved
105	--	skipped
120	--	Did not achieve – catastrophic scouring – STOPPED
140	--	not tested
[1]Module Weight prior to test (lbs):		38.31
[1]Module Weight following test (lbs):		35.29
[2]Total Module Weight loss following test (lbs):		3.02
[3]Calculated weight of collected materials (gms):		1141.68

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day Two Test #9 (18 inch x 18 inch green roof model with vegetative coverage – treated with Liquid Binding Agent A)

Test Setup:

An 18 inch x 18 inch green roof module containing a growth media mixture comprised of 80% Arkalyte (3/8 inch aggregate) and 20% composted pine bark was planted 60-days previous to testing with Sedum plugs and Sedum cuttings was treated with a liquid binding agent (Liquid Binding Agent A 1:1 chemical:water) 48 hours prior to wind tunnel testing. This vegetated and "treated" module was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

Though test #7 clearly demonstrated the effectiveness of the Liquid Binding Agent A in binding the surface of the growth media to control wind scour on non-vegetated areas of a green roof, the test was repeated with a module that had been propagated using Sedum plugs and Sedum cuttings to determine if the plant material impeded the ability of the applied liquid chemical to bind the growth media particles under and around the plant material. During the test, growth media and vegetation remained largely stable with very little notable displacement throughout nine minutes of testing that concluded after the five minute duration at 140 mph. A minimal amount (40.12 grams) of growth media and plant material was collected from the testing chamber at the conclusion of the test. The group will "grow out" this module to evaluate at a later date any phyto-toxicity of the Liquid Binding Agent A.

Table 18. Wind tunnel conditions and results during Test #9 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	--	skipped
75	--	skipped
90	2	achieved
105	--	skipped
120	2	achieved
140	5	achieved
[1]Module Weight prior to test (lbs):		33.10
[1]Module Weight following test (lbs):		32.72
[2]Total Module Weight loss following test (lbs):		0.38
[3]Calculated weight of collected materials (gms):		40.12

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day Two Test #10 (two green roof fabric models with NO vegetative coverage and a wind deflector)

Test Setup:

Two (24 inch x 32 inch) five-inch deep fabric green roof module with no vegetative coverage and no openings in the modules for planting were placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. A wind deflector was placed in front of the leading module. The downwind green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

Turbulence within the two modules allowed growth media to migrate within the fabric enclosure beginning at 105 MPH and accelerating until catastrophic module displacement at just over 120 MPH (approximately 125 mph when raising the wind speed to 140 mph).

Table 19. Wind tunnel conditions and results during Test #10 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	5	achieved
140	--	not tested
[1]Module Weight prior to test (lbs):		not determined
[1]Module Weight following test (lbs):		not determined
[2]Total Module Weight loss following test (lbs):		not determined
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day Two Test #11 (two green roof fabric models with freshly planted Sedum plugs and a wind deflector)

Test Setup:

Two (24 inch x 32 inch) five-inch deep fabric green roof module from test #10 were placed in the wind tunnel directly on the EPDM roofing membrane oriented squarely with the leading side perpendicular to the wind source. A wind deflector was placed in front of the leading module. Six small slits were cut in the top of each of the fabric modules and each slit was planted with a mixed species Sedum plug (72s) just prior to the wind tunnel test. The downwind green roof module was tethered with a rope to ensure that if the module was displaced during testing it would not damage the testing equipment. The tether provided enough slack in the rope to allow ample movement of the module to determine any point of failure.

Additional Observations:

Testing was initiated at 90 mph and intended to go directly from 90 mph directly to 120 mph. The growth media and vegetation remained stable throughout the two minute duration at 90 mph. Shortly after beginning the increase from 90 mph to 120 mph, turbulence began building above the surface of the growth media under the top surface of the leading fabric module. In the leading module, aggregate began to percolate around the Sedum plugs and erupt through the openings that were cut into the fabric. The test was concluded prior to reaching wind speeds of 105 MPH.

Table 20. Wind tunnel conditions and results during Test #11 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	--	skipped
75	--	skipped
90	2	achieved
105	--	stopped prior to achieving
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		not determined
[1]Module Weight following test (lbs):		not determined
[2]Total Module Weight loss following test (lbs):		not determined
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day Two Test #12 (18 inch x 18 inch green roof model with NO vegetative coverage and a netting covering growth media)

Test Setup:

A 18 inch x 18 inch green roof module filled with a growth media mixture comprised of 80% Haydite (3/8 inch aggregate) and 20% composted pine bark was covered with a netting material (provided by a green roofing company). The netting material was stretched over the top of the growth media, turned down the sides of the aluminum module, and secured with duct tape. The 18 inch x 18 inch module containing growth media only and covered with the netting material was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

Though the netting material was supplied to the research team to be tested as a wind control strategy, no installation or anchorage instructions were provided. Securing the material to the aluminum module with duct tape limited the test to evaluating the material's ability to contain the growth media under wind load. Prior to achieving the 60 mph wind speed large amounts of growth media readily passed through the netting material and became windborne (catastrophic failure occurred at approximately 50 mph).

Table 21. Wind tunnel conditions and results during Test #12 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	--	not achieved – shut down @ 50 mph
75	--	not tested
90	--	not tested
105	--	not tested
120	--	not tested
140	--	not tested
[1]Module Weight prior to test (lbs):		not determined
[1]Module Weight following test (lbs):		not determined
[2]Total Module Weight loss following test (lbs):		not determined
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Wind Tunnel Day Two Test #13 (18 inch x 18 inch green roof model with NO vegetative coverage and burlap covering growth media)

Test Setup:

A 18 inch x 18 inch green roof module filled with a growth media mixture comprised of 80% Haydite (3/8 inch aggregate) and 20% composted pine bark was covered with a 100% natural burlap. The burlap was stretched over the top of the growth media, turned down the sides of the aluminum module, and secured with duct tape. The 18 inch x 18 inch module containing growth media only and covered with the burlap was placed in the wind tunnel directly on the EPDM roofing membrane oriented at a 45 degree angle with a corner facing the wind source. The green roof module was tethered tightly with a rope to ensure no module displacement during testing. The module was additionally secured to the EPDM roofing membrane with duct tape on both the leading edges to prevent wind uplift of the module.

Additional Observations:

Securing the burlap to the aluminum module with duct tape limited the test to evaluating the material's ability to contain the growth media under wind load. The burlap material contained all growth media throughout all targeted wind speeds and durations through 105 mph. Obstruction in the pitot tube in the wind tunnel prevented the documentation of wind speed target at 140 mph. After more than five minutes at wind speeds estimated using the electrical input to the fan motor exceeding 140 mph, the test was concluded.

Table 22. Wind tunnel conditions and results during Test #13 on 8/9/2009.

Wind Velocity (mph)	Test Duration (min)	Observation
60	1	achieved
75	1	achieved
90	2	achieved
105	3	achieved
120	--	skipped
140	--	obstruction of Pitot tube – ran for 5 minutes, but not able to reach appropriate speed
[1]Module Weight prior to test (lbs):		not determined
[1]Module Weight following test (lbs):		not determined
[2]Total Module Weight loss following test (lbs):		not determined
[3]Calculated weight of collected materials (gms):		not determined

Note[1]. Entire modules were placed on an OHaus Scale (Model CD-11, Load Frame Champ Square CQ50L) and weighed before and after completion of each test.

Note[2]. Total module weight loss = module weight prior to test – module weight following test.

Note[3]. Debris on the screen at the end of the wind tunnel was vacuumed and placed in a Ziploc bag and weighed on an Ohaus Explorer balance (Model EOD120) to calculate the loss of materials "blown off" each green roof model.

Conclusions

Hypothesis #1 – Four inches of fully vegetated growth media can sustain two minute wind gusts greater than 90 MPH.

Yes, fully vegetated modules in day one testing (test #1, test #2, and test #3) and in day two testing (test #5) all reached wind speeds of 120 mph (for 5 minutes) with no displacement of growth media.

Hypothesis #2 – There is a minimum level of vegetation required to bind the growth media in order to resist scour during two minute wind gusts greater than 90 MPH. Identify that level.

Yes, there is a minimum level of vegetation required to bind the growth media. In all tests with partially vegetated modules (vegetated prior to testing), scouring of growth media occurred after reaching wind speeds of 75 mph in these tests. In tests using only growth media, scour occurred at wind speeds as low as 30 mph. As above, 100% vegetation coverage or a "binding agent" is necessary to "bind" the growth media to prevent scour at wind speeds above 75 mph.

Hypothesis #3 – There are surface treatments that are effective in minimizing scour at various wind speeds. Identify the treatment and the wind speed at which it is no longer effective.

Yes, two of the five methods ("binding agents") tested prevented wind scour of growth media. No wind scour was observed at 140 mph when Liquid Binding Agent A (day two test #7) had been applied to a module containing only growth media 48-hours prior to testing. In addition, no wind scour was observed at 140 mph when Liquid Binding Agent A (day two test #9) had been applied to a partially-vegetated module 48-hours prior to testing. No wind scour was observed below 90 mph when Liquid Binding Agent T (day two test #7) had been applied 48-hours prior to testing. Further, no wind scour was observed to speeds above 120 mph when 100% natural burlap was used as a "surface treatment".

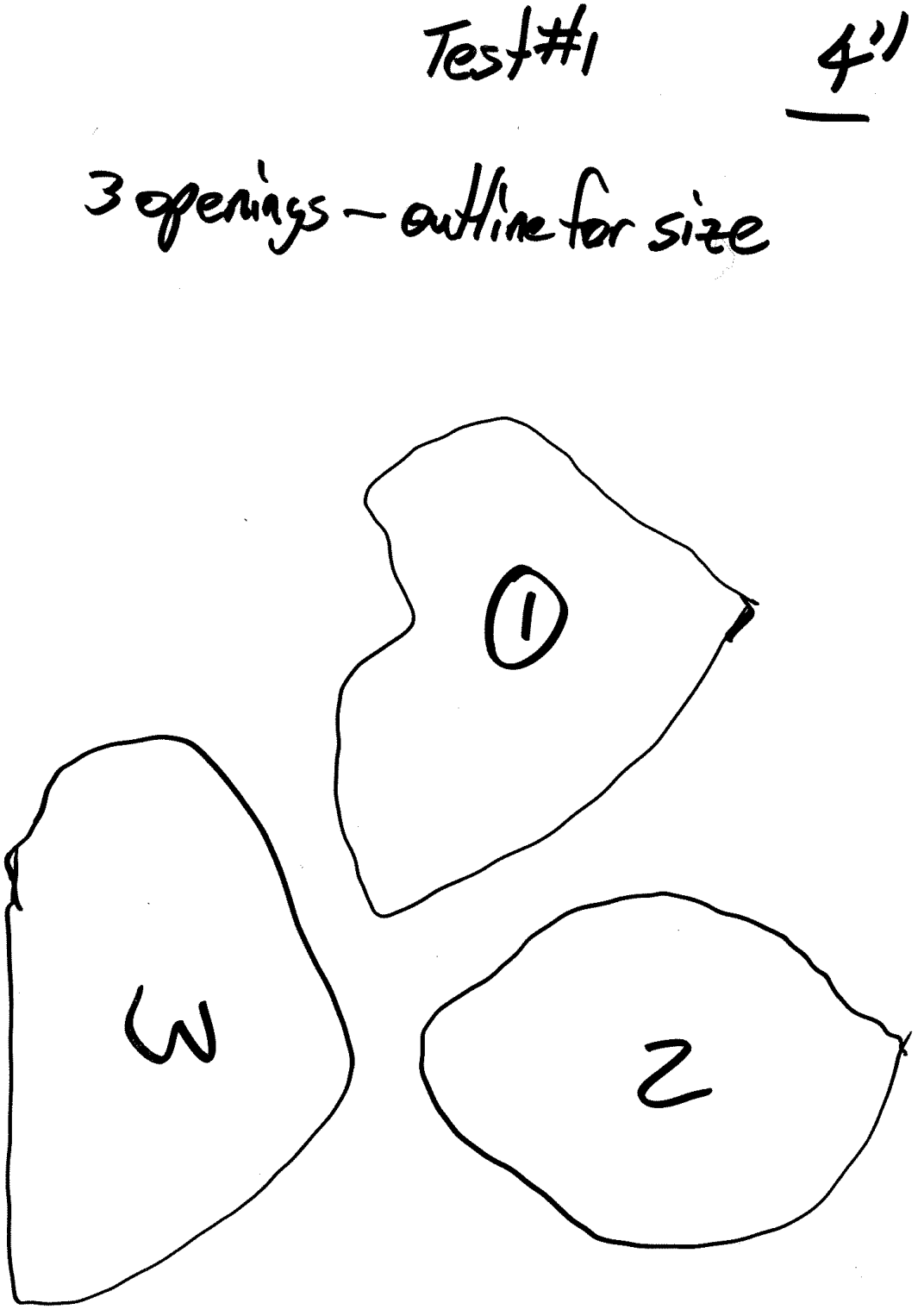
Literature Cited

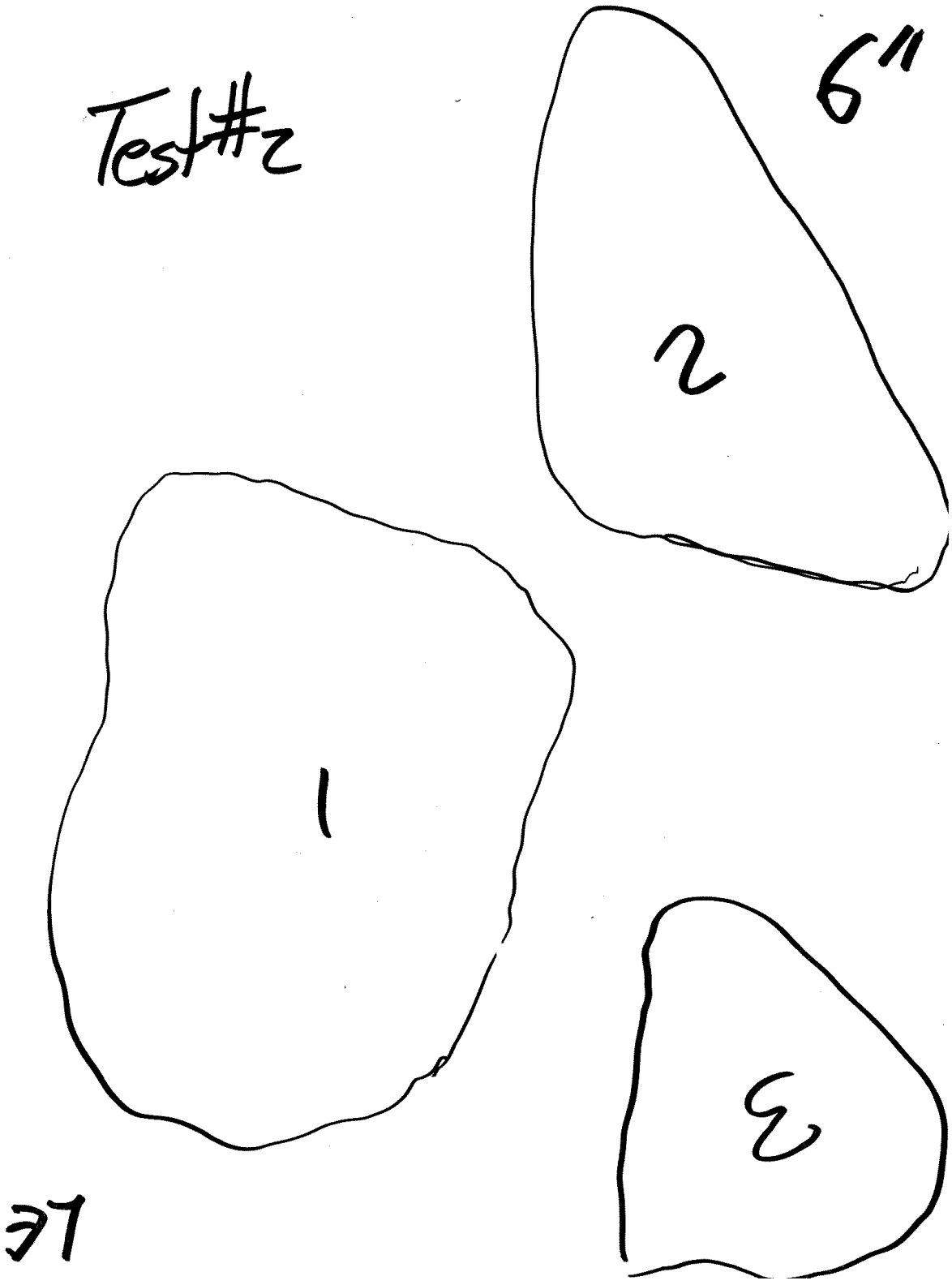
Forrester, Krista. 2007. *Evaluation of Storm Water Runoff from a Midwest Green Roof System.* (Thesis) Southern Illinois University Edwardsville, Edwardsville, IL. pp.

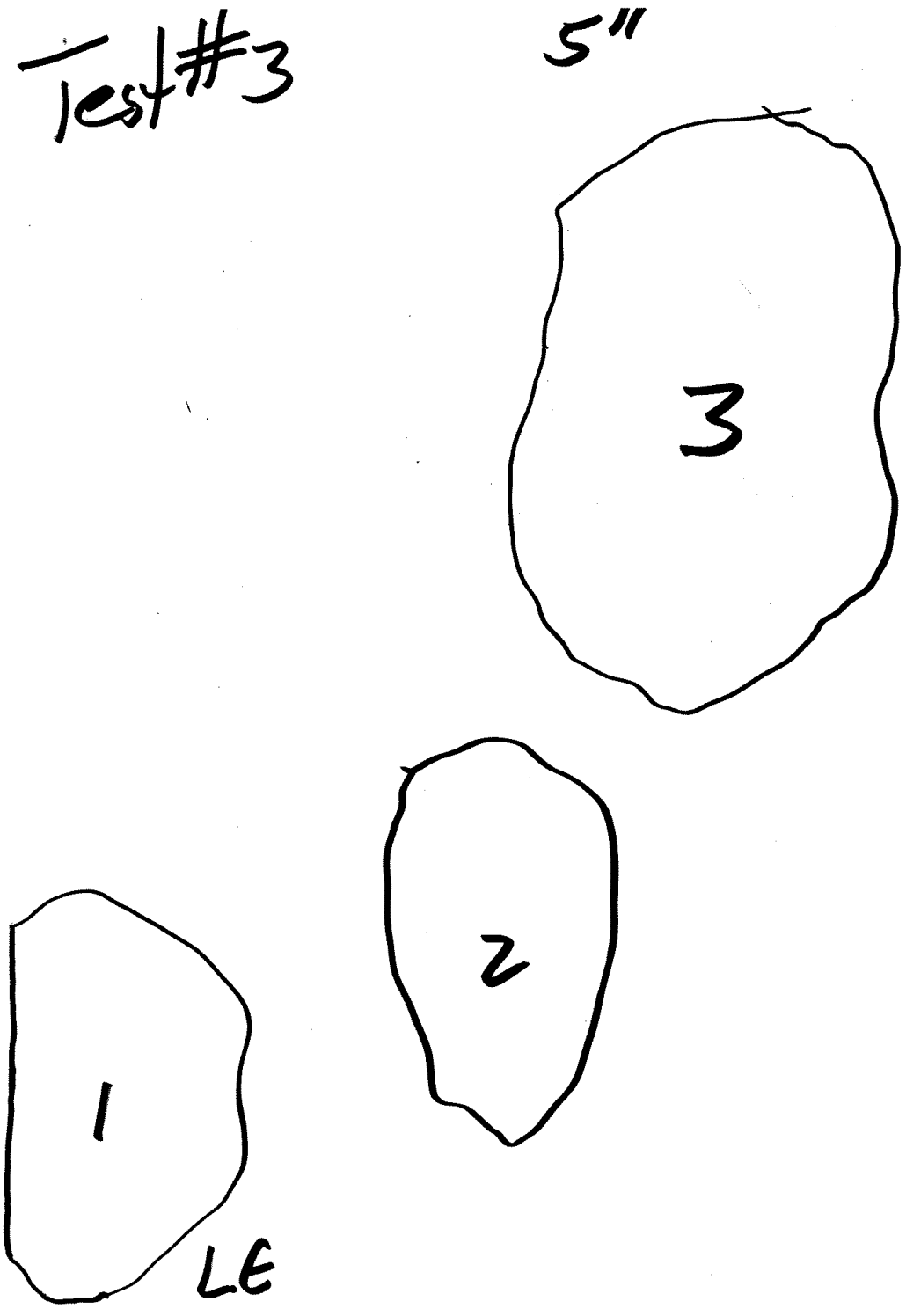
Appendix 1

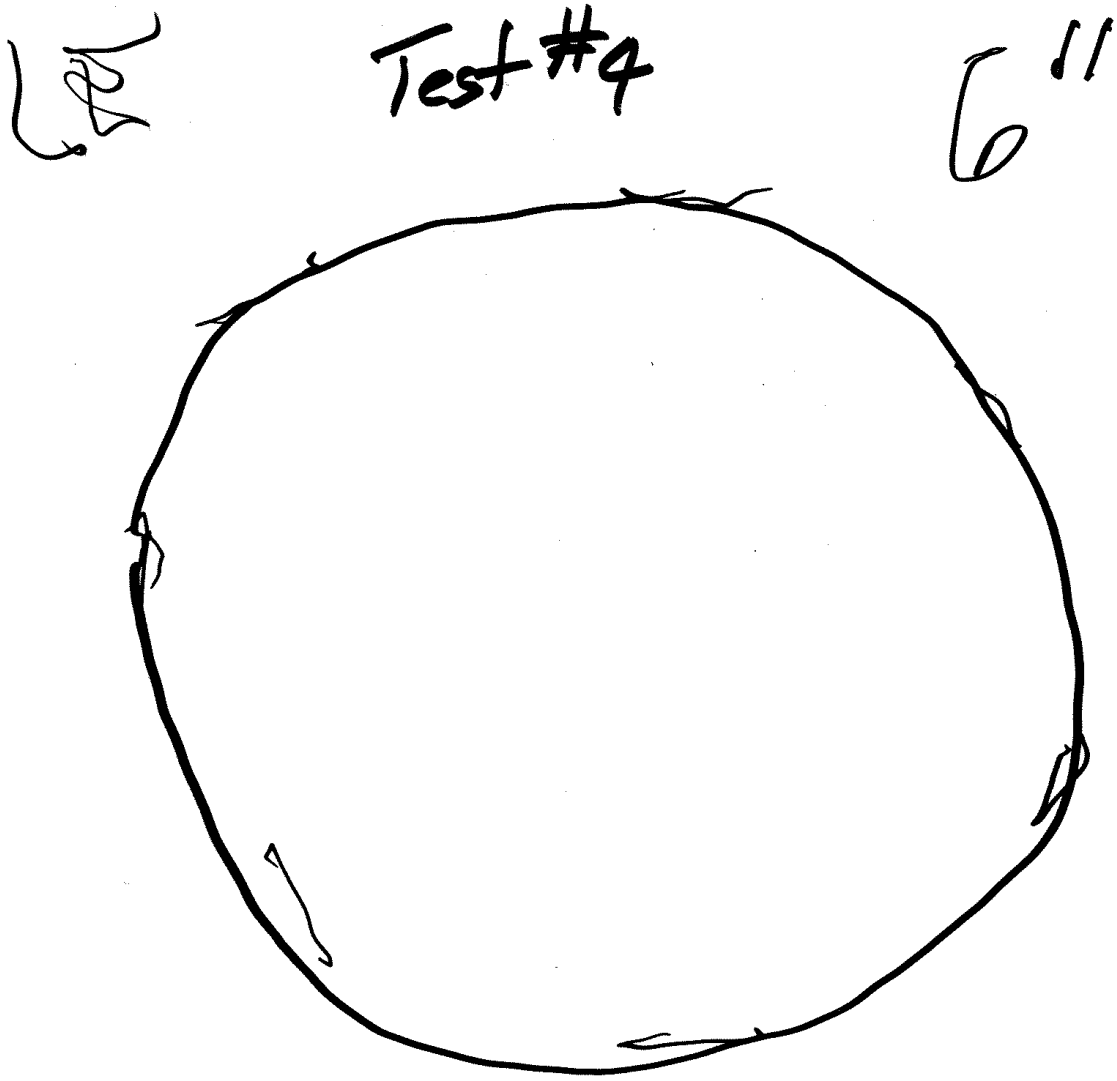
The end cap was removed from the exhaust side of the wind tunnel and a metal closure was installed to allow exhaust air to exit the tunnel while allowing outside air to enter the intake duct. The metal closure revealed a lack of dimensional stability during the first test run of the blower fan. Augmentations were made to the metal closure to achieve the necessary stability to allow the blower fans to run at maximum capacity. However, the wind speed generated by the blower fan as indicated by the internal pressure gauges and verified by handheld anemometer were significantly less than the documented capacity. We were informed during a telephone conversation with a technical support representative for the wind tunnel manufacturer that removing the end cap from the exhaust end of the wind tunnel reduces the capacity of the blower fan as the air forced into the intake by the exhaust is critical for the fan to achieve maximum output. Once the end cap was reinstalled, wind speed capacity was restored to previously documented levels.

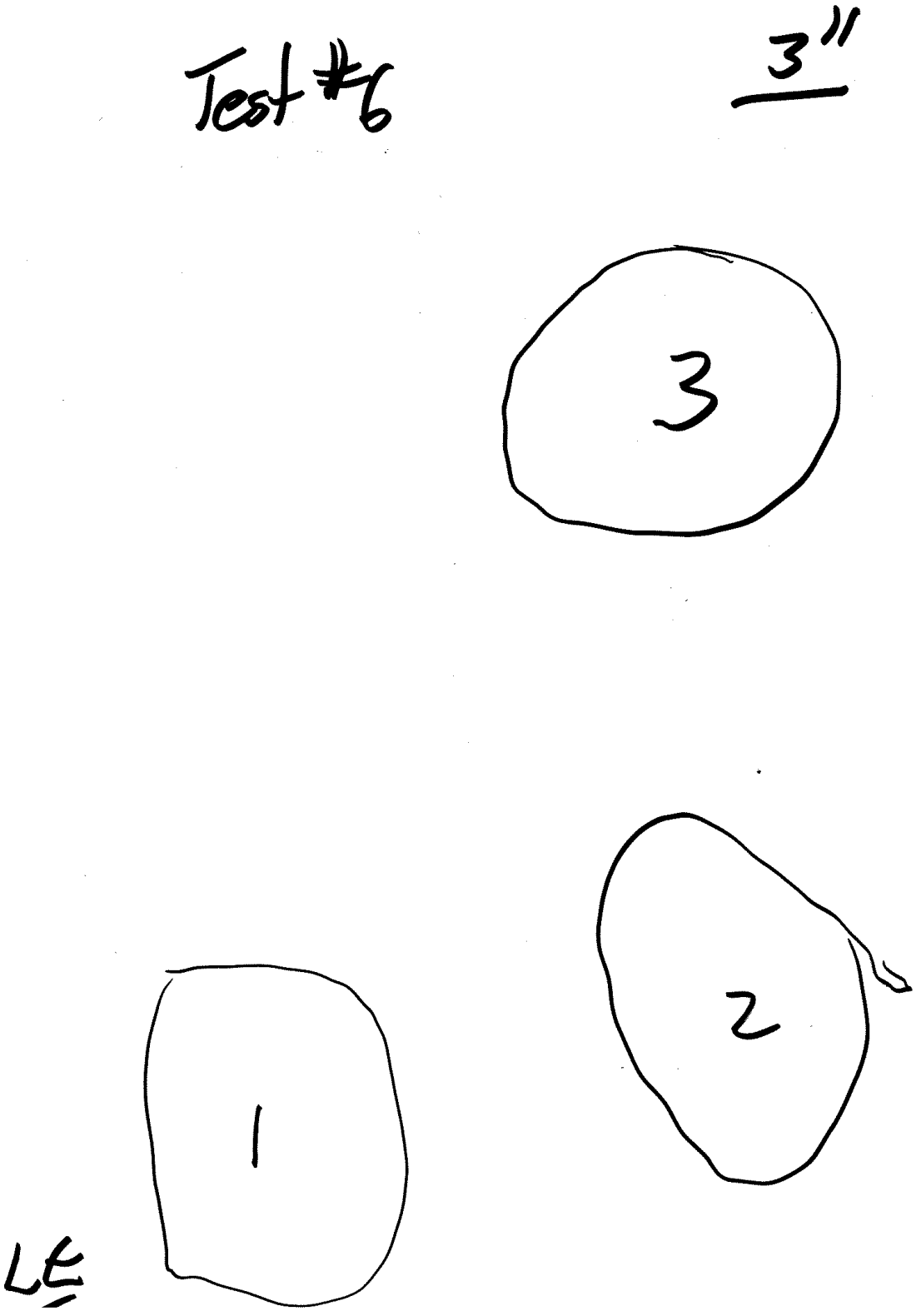
Appendix 2




Test #2
6"
2
1
3
37


Test #3
5"
3
2
1
LE


Test #4
6"


Test #6
3"
3
2
1
LE

Appendix 3

Growth Media Data Sheet

TABLE 1 Gradation Requirements for Aggregate (ASTM C330-C331)

Sieve Specification	Extensive Green Roof Gradation (% Passing)
19 mm (3/4 in.)	**100**
12.5 mm (1/2 in.)	**100**
9.5 mm (3/8 in.)	**90-100**
4.75 mm (No. 4)	**65-100**
2.36 mm (No. 8)	
1.8 mm (No.16)	**40-80**
0.6 mm (No. 30)	
0.3 mm (No.50)	**10-35**
0.15 mm (No. 100)	**5-25**
0.074 mm (No. 200)	**0-20***

* **The percentage of material passing 0.074 mm by vol. also applies to any components including organic matter used as an amendment to the aggregate.**

2.5.2 Physical Properties: the aggregate shall conform to the physical properties specified in Table 2.

TABLE 2 Physical Properties of Aggregate

Physical Properties	Unit	Value	Test Method
Bulk Density Dry Loose	lbs/cf	38 – 70	ASTM C 29
Bulk Density (max. water holding capacity)	Ibs/cf	< 90.0	ASTM C 29
Maximum Index Density	SSD lbs/sf	< 78	ASTM D 4254
Total Volume of Voids	Vol. %	> 10.0	ASTM C 29/ C29M, see note 1
Air Filled Porosity	Vol. %	> 10.0	ASTM E 2399
Maximum Water-holding Capacity	Vol. %	> 35.0	ASTM E 2399
Water Permeability	cm per sec	> 0.001 cm/s	ASTM E 2396
Angle of Internal Friction (Compacted)	Degree	32 º – 40 º	ASTM D 4764
Frost-resistance	% Loss	< 5%	ASTM C 88
Los Angeles Abrasion	% loss by wt.	NA	ASTM C-131 modified method FM 1-T096

Apparent Density	
soil mixture (g/cm^3)	
aggregate mixture (g/cm^3)	0.8 (47.3 pcf)
at Maximum Water Capacity	
soil mixture (g/cm^3)	
aggregate mixture (g/cm^3)	1.0 (61.5 pcf)
dry density (g/cm^3)	0.7 (45.7 pcf)
Water and Air Management (% Volume)	
total pore volume	45
maximum water capacity	35
air content at maximum water capacity	10
air content at 1/3 atm.	18
Water Permeability (cm/sec)	0.05 (0.02 in/sec)
pH, Lime , and Salt Content	
pH (in $CaCl_2$)	7.5
carbonate content (g/l)	3.9
salt content (g/l)	1.5
Organic Substances	
organic content (% weight)	4.7
C/N ratio	10
Nutrients (plant available, mg/l)	
nitrogen (NO_3+NH_4)	61
phosphorus	159
potassium	650
magnesium (in $CaCl_2$)	405
Absorptive Capacity (mmols/Z/l)	145

"Methods for Soil Analysis" Forest Soil Coordinating Center (FSCC), 2003
Agriculture Handbook No. 60, United States Department of Agriculture, 1954

Data for Blended Growth Media

Composition:

Kiln Fired Expanded Clay 80% (by volume)
Composted Pine Bark 20% (by volume)

Dry Weight	33 pcf
Saturated Weight	54 pcf
Water holding capacity	21pcf (2.52 gallons)

Recommended Fertilization

Annual application of granular at 5 pounds per 5000 sq ft
Balanced nutrients 15-9-12
12-14 month release or longer