Modular Green Roof Systems in Mid-rise Multifamily Residential Units

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ABSTRACT

This paper presents the results of a full-scale research project undertaken to assess scour losses/gains for modular tray green roof specimens placed on a mock-up building, and identify important factors to consider for wind design criteria. Visual assessment of the experimental results showed that usage of vegetation, parapet height, wind direction, and test duration were the predominant factors affecting scour resistance of the growth media in tested specimens. Statistical analysis results indicated that the differences in soil losses measured among Phase 2's test trials were more significant than those in Phase 1. This was attributed to the lack of parapet, cornering wind conditions, and longer test duration found in Phase 2. Findings presented in this paper constitute a benchmark for future research to improve the knowledge gap that exists in green roof wind design.

BACKGROUND

The housing sector accounts for a large and growing portion of the built infrastructure within cities worldwide, and in the global context, urban populations surpassed rural populations for the first time in 2008. It is projected that by 2050, there will be a 70 percent increase in global urban populations (UN Populations Division 2008). From the U.S. perspective, most of its population currently live in single-family residential structures (in over 100 million homes) (U.S. Census Bureau and American Community Survey 2012), but current trends suggest that an increasing number of people will live in urban multi-family complexes. This change will provide opportunities to construct structures that are more sustainable, resilient to natural hazards (wind, seismic, floods), and responsive to growing urban population needs.

On the other hand, higher density (multi-family) housing can present some drawbacks, two of which are increased *urban heat island* effects and increased stormwater runoff, both triggered by the alteration of the natural landscape. Green (or vegetative) roofs offer a solution to several urban issues as they can be installed on new or existing, impervious low-slope roofs for commercial and residential buildings to increase the vegetation footprint in urban environments with otherwise limited open areas. Further, large-scale implementation of green roof systems help to effectively alleviate urban heat island effects, as opposed to single-roof installations (Bass 2012). Green roofs can potentially reduce stormwater runoff, increase biodiversity, and prolong the service life of the underlying roofing system (Saiz et al. 2006).

Green roof systems are multi-layer assemblies typically consisting (from top to bottom) of live vegetation, growth media, filter fabric, optional root barrier, drainage layer, and a waterproofing membrane. The growth media is classified by its depth, as either intensive (greater than 150 mm [6 in.]), or extensive (less than 150 mm [6 in.]). This classification dictates the types of plants that are suitable for the green roof system, as well as the structural details of the supporting roof structure. Green roofs can be installed either as built-in-place (continuous) roofing or modular tray systems assembled in a grid using rectangular metal or plastic-polymer containers. The installation of a modular tray green roof is similar to that of roof pavers in that discrete units are placed on the roof and provide protection and the gravity load (ballast) that holds the roofing membrane in place. Modular green roofs are subject to similar failure mechanisms that roof pavers are in extreme winds. And while modular tray roofs may have the advantage of more efficient installation and maintenance over built-in-place green roof systems, their installation in discrete modules may also increase the risk of wind uplift failures, a risk that until recently has not yet been evaluated.

Green roof history. The contemporary green roof movement began in the U.S. around the mid-1990s, through adaptation from Europe's (mostly Germany's) green roof industry. The green roof industry gained popularity in the U.S. after a green roof was installed on Chicago's City Hall Building in 2001 and on the roof of Ford Motor Company's River Rouge Plant in Dearborn, MI in 2003. Since then, the growth has concentrated in metropolitan areas like Chicago, IL, Washington, DC, and New York, NY. Currently, approximately 6,500 m^2 (70,000 ft^2) of green roofs have been installed in Florida (a hurricane-prone state) since 2001, compared with the 126,000 m^2 (1.3 million ft^2) of green roofs that were installed in Chicago and Washington, DC in 2011 alone (Green Roofs for Healthy Cities 2012; Greenroofs.com 2012). The limited number of Florida green roofs may be traced to the high design wind speeds in Florida and the lack of a wind design guide for these systems. Further, the Florida Building Code has strict requirements mandating submission of wind resistance evaluation reports for any building envelope element to be installed on a building. Currently there are no accepted test protocols for evaluating the wind resistance of green roof systems.

The first wind-performance tests reported for green roof systems were conducted on modular and built-in-place green roof systems by Retzlaff et al. (2010) and Wanielista et al. (2011), respectively. Their results established that the presence of fully established plants effectively mitigates growth media scour at high-wind speeds. Although, they are not adopted by any building code, there are two wind design guides for green roof systems in use for the United States; the ANSI/SPRI RP-14 (ANSI/SPRI 2010) and Factory Mutual's FM 1-35 (FM Global 2011). Although the wind tunnel study of Retzlaff et al. (2010) was referenced by the RP-14, its design specifications are based on earlier wind design provisions – RP-4 (ANSI/SPRI 2008). No full-scale tests were used in development of the RP-14 provisions. Thus, validation of the RP-14 design guideline has yet to be carried out.

Wind loading on flat roofs. Wind flow around a building produces spatially and temporally varying wind pressures on the walls and roof of a building. It is well-known that roofing systems can be damaged by the high suctions occurring at the corner regions and edges of a roof. Bienkiewicz and Sun (1992) showed that cornering winds on buildings (i.e. wind direction not parallel to a building edge) resulted in the production of conical vortices above the roof and commensurate extremely high suction forces. Such effects are known to cause failures of roof pavers via uplifting and sliding on roofs. It is therefore likely that similar failures would occur with green roof systems, particularly those that rely solely upon gravity loads to keep the roofing system in place. Another failure mechanism with green roofs is the scour loss of plants (vegetated materials) and growth media. These failures are analogous to the losses occurring in gravel ballasted roof systems that were the subject of several roof studies from the 1970s to late 1980s (Wardlaw and Kind 1985). Those studies clearly demonstrated the destructive power of conical vortices. More recently, Karimpour and Kaye (2012) described a potential problem whereby extreme winds may move roof gravels and other granular material around a roof, which could result in overloading sections of the structural system.

To further understand how green roofs perform under realistic wind loads, the authors conducted a two-year study evaluating wind effects on modular tray and built-in-place green roof systems. The goal of this study was to define pertinent features of a wind uplift design guide for the green roofs installed in Florida (Vo et al. 2012). Supported by the Florida Building Commission's Hurricane Research Advisory Committee, the analyses in this study compasses multiple design criteria such as local plant selection, and the performance of green roofs under extreme simulated wind speeds. Complementary statistical analysis of the wind-induced scour losses of modular tray green roof specimens are provided in addition to visual assessment of the wind experiments.

METHODS AND MATERIALS

Tests were conducted using a model building (measuring 2.4 m x 2.4 m x 2.4 m tall [8 ft. x 8 ft. x 8 ft.]) placed approximately 3.7 m (12 ft.) downstream of a hurricane simulator (Figure 1). The hurricane simulator generated test wind speeds using eight-1.5 m (5 ft.) diameter vane-axial fans to produce a 3 m x 3 m (10 ft. x 10 ft.) air jet at wind speeds up to 54 m/s (120 mph). The simulator also includes vertical fins that rotate side-to-side to simulate lateral turbulence. However these fins were not used in this experiment, resulting in unnaturally low turbulence intensity (Masters et al. 2008).

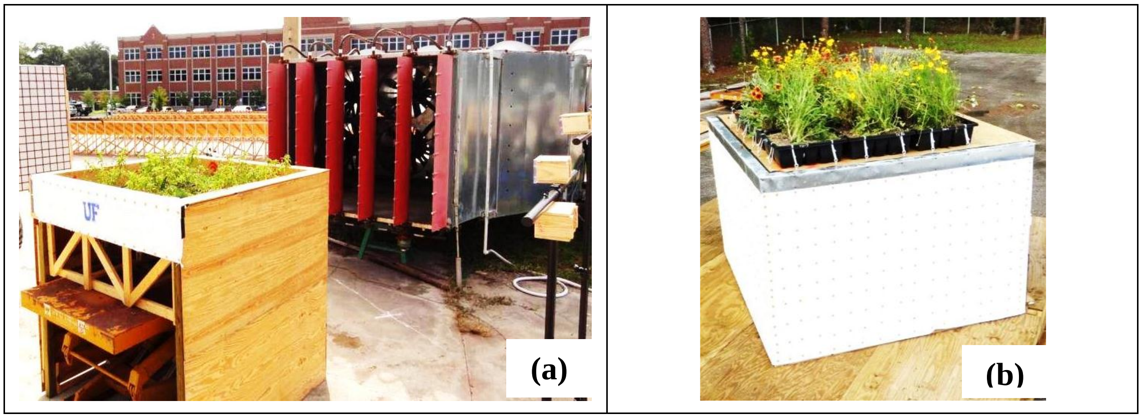

Figure 1. (a) Building at 90° wind azimuth (b) Building at 45° wind azimuth

Wind testing of the modular tray green roof specimens was divided into two phases (Table 1), with each test having nine 0.6 m by 0.6 m (24 in. by 24 in.) modular trays. Phase 1 tested eight planted and one unprotected (bare growth media tray) modules, and the wind flow was perpendicular (at 90°) to the front wall. The location of the unprotected module was varied between the six test trials to compare the specimen performances and identify the roof areas prone to high scour. Also, the building mock-up included a 300 mm (12 in.) high parapet. In Phase 2, the parapet was removed and the building was oriented to produce a 45° cornering wind direction, and some specimens from Phase 1 were re-tested in this configuration.

Modular tray specimens were weighed just before being placed on the deck of the mockup building for testing, and their positions were noted (Figures 2 and 3). Each nine-tray array of modules was then tested, and the plant and growth media behaviors were observed and recorded using three video- and still-cameras. The module tray specimens were weighed again following each wind test trial to determine the losses incurred.

Table 1. Comparison of Phase 1 and Phase 2 test parameters

	Phase 1	**Phase 2**
Successful test trials	6	6
Modular tray specimens*	54 (6 unprotected)	72 (0 unprotected)
Wind direction	0°	45°
Parapet	300 mm	0 mm
Plant heights	Mixed	Mixed (retested), tall, short
Establishment	3, 5, & 9 months	6 & 13 months
Wind speed	9 – 54 m/s	45 m/s
Test duration	5 minutes	10 or 20 minutes

*Unprotected: No vegetation, liquid binder, or erosion control mat.

GRAPHICAL RESULTS

A graphical representation of specimen weight differences in growth media and its relation to the roof locations and weight averages (denoted by the horizontal red line), are presented in Figures 4 and 5. Weight differences were taken as the final specimen weight minus the initial specimen weight. Tests were denoted as Stat IDs, and will be referenced as the latter term in the later sections. Visual assessment indicated four factors affecting the scour resistance of the green roof specimens: parapet height, growth media protection (i.e. planted vs. unplanted conditions), wind direction, and test duration.

Parapet height. The presence of the parapet in Phase 1 reduced growth media blowoff but resulted in substantial redistribution of growth media, depending on the location of the unprotected specimen. Growth media redistribution is most clearly represented in Tests 1.1 and 1.4 in Figure 4, where weight gains of 2.26 kg (4.98 lbs; 12 % increase) and 2.70 kg (5.95 lbs; 7% increase), were measured in roof locations 6 and 4, respectively. This contrasts with the results in Tests 2.1 – 2.6 (Figure 5), as observed instances of weight gains were rare and insignificant. Usage of a parapet in Phase 1 protected the windward row of specimens from direct wind exposure, but introduced a flow reversal along the inboard face of the leeward parapet (except in Test 1.6 where the leeward parapet was removed). This reversal can be observed by comparing plots for Tests 1.1 and 1.4 from Figure 4 with the plots for Tests 2.2 and 2.5 from Figure 5.

For Phase 2 tests, growth media losses were more pronounced in the leading corner specimen (Tests 2.2 and 2.5 of Figure 5), due to the increased wind flow at roof level with no parapet in place. Further details on the testing and results can be found in Vo et al. (2012).

Protected (planted) modules. Scour resistance of green roof specimens is directly related to their vegetation coverage. Vegetation coverage is provided by both the vegetation foliage/stems (captured by overhead photography) and planting density (i.e. number of plants per area and captured by frontal photography normal to the plant height). Retzlaff et al. (2010) showed that specimens with 100% vegetation coverage (overhead) were able to resist media scour for wind speeds up to 63 m/s (140 mph). This applicability of their result is limited since Retzlaff et al. did not simulate realistic turbulent wind flows and they only tested a single module tray installed within an aerospace wind tunnel. The present study calculated coverage ratios obtained from overhead photographs taken before and after wind testing in Phase 2.

Tests 2.1, 2.2, and 2.5 (Figure 4) resulted in the most observable weight losses in Phase 2. Thus, to identify any relationship between coverage and scour losses, their coverage ratios were summarized in Figure 6. It can be seen that Tests 2.2 and 2.5 (Figure 6), which shared identical types of vegetation and a comparable establishment period (but with different media depths), produced plots which differed from one another in Figure 4. This could be explained from the difference in vegetation coverage and height between the two tests. The greater vegetation height and coverage in Test 2.5 resulted in more effective sheltering of loose media, and reduced growth media losses further downwind of the array when compared to Test 2.2.

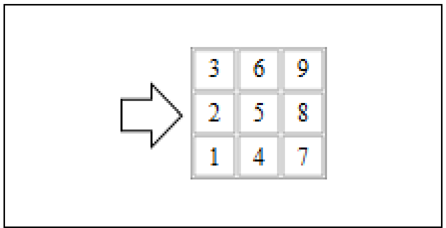

Figure 2. Phase 1 location IDs

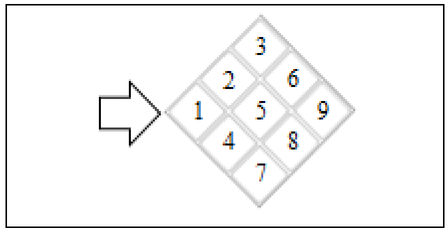

Figure 3. Phase 2 location IDs

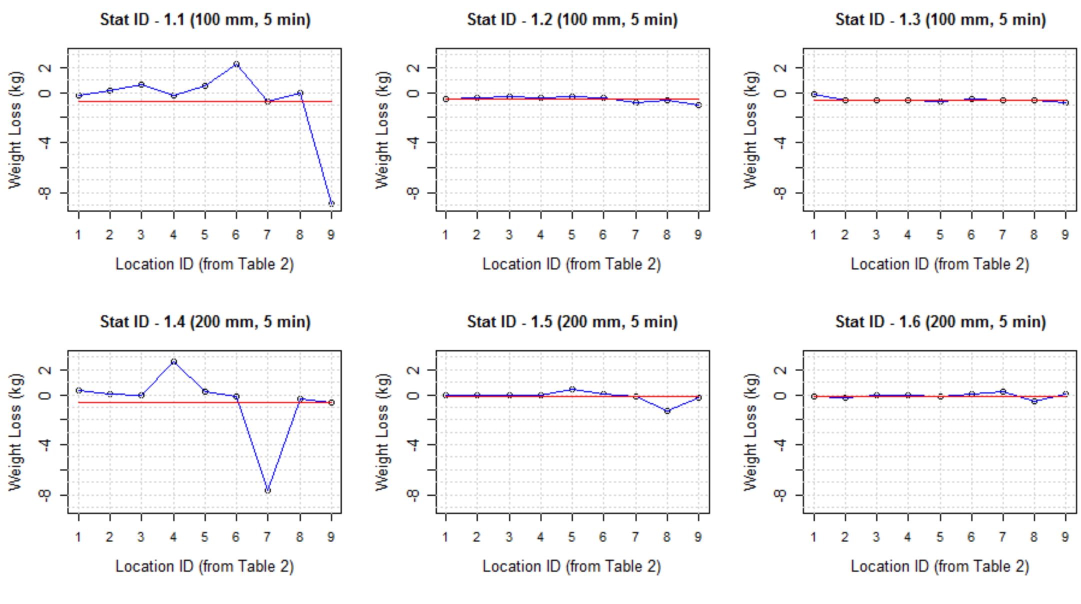

Figure 4. Phase 1 weight differences plotted against corresponding averages

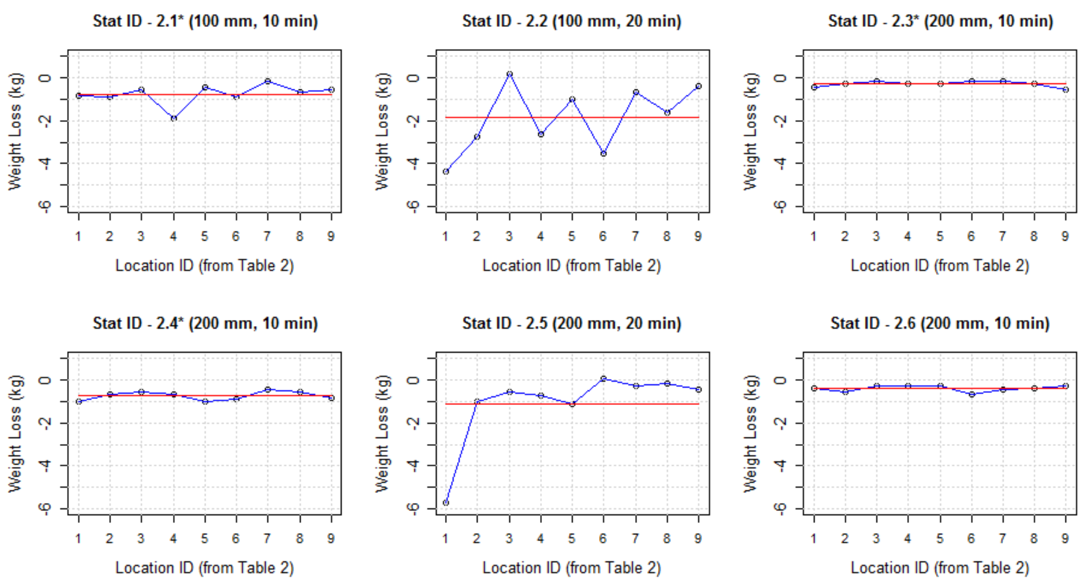

Figure 5. Phase 2 weight differences plotted against corresponding averages. *Modular specimens re-tested from Phase 1 were in identical locations.

Wind direction and test duration. Determination of the effects due to varying the wind azimuth between Phase 1 and Phase 2 was not possible due to the inclusion of a parapet in Phase 1, while none was used in Phase 2. However, Test 2.2 (Figure 5) displays measurable losses in array locations, which suggest the presence of conical vortices. This is further reinforced by the plant bending patterns addressed in an earlier article by the authors (Vo et al. 2012). Present results suggest that longer test durations produced higher losses (as shown in Tests 2.2 and 2.5 from Figure 5), but because vegetation type and age varied throughout, this observation cannot be generalized without further analysis of statistical significance.

Stat ID	2.1	2.2	2.5
Before Wind Tests			
	64.5%	59.2%	77.9%
After Wind Tests			
	61.2%	52.6%	62.7%

Figure 6. Coverage ratios in Phase 2 for Tests 2.1, 2.2 and 2.5.

STATISTICAL RESULTS

To assess the impact of different environmental settings and green roof properties, comparative statistical analyses through different strata of project settings were completed on successful test trials. The uncontrolled factors between test trials (i.e. wind test duration, plant type, usage of unprotected module, etc.) in combination with the small number of experimental tests presented a limited sample pool for conducting a statistical analysis. Therefore, non-parametric comparative analyses were conducted for two cases: specimen weight differences' relation to corresponding experimental means and overall weight differences between test trials of similar variables. Test scores for different exercises will indicate different significance thresholds, thus standardized with the p-values shown in Tables 2 and 3. For both sets of comparative assessments, the null hypothesis (i.e. no difference between test samples) is rejected if the probability is less than 5%.

Table 2 presents the first set of comparative assessments used to determine the significance of the differences between the pre- and post-test weights of individual modules in each test trial. Because the overall weights were not independent of each other (i.e. gains from one specimen as a result of the losses from another), a paired analysis of the pre- and post- weights is more suitable for the data set under consideration. Non-parametric Wilcoxon signed rank-sum tests were used to test the specimen weights. Non-parametric analyses, unlike more common parametric statistics, do not rely on assumptions such as normality and are therefore more flexible (Hoskin), and considering the smaller sample size of the data points, they were adopted over more traditional parametric statistics.

The results from Table 2 state that significant differences *were* present between pre- and post- test weights for Tests 1.2, 1.3, and 2.1 – 2.6. When these results are compared against results in Figures 4 and 5, it is apparent that test trials which experienced net losses (i.e. test trials where more growth media blow-off occurred than redistribution) might have resulted in statistically significant differences between their specimens' pre- and post- test weights. Thus, the usage of a parapet during testing resulted in less significant differences in specimens' weights.

Table 2. Comparison of data between specimens within each experiment

Stat ID	Statistical Test	Test Score	p-value
1.1	Wilcox	24	.91
1.2	Wilcox	45	.004*
1.3	Wilcox	45	.004*
1.4	Wilcox	26	.73
1.5	Wilcox	26	.29
1.6	Wilcox	34	.20

Stat ID	Statistical Test	Test Score	p-value
2.1	Wilcox	45	.009*
2.2	Wilcox	44	.008*
2.3	Wilcox	45	.009*
2.4	Wilcox	45	.004*
2.5	Wilcox	44	.008*
2.6	Wilcox	45	.009*

*Null hypothesis rejected

Table 3 presents results from the second set of comparative tests conducted to assess the differences in observed soil losses for similarly-constructed test trials (i.e. same wind speeds and test durations, etc.). Provided the test setups had consistent treatments, it was assumed that there should be no statistically significant difference in the soil loss observed between the experiments for specimens placed in the same roof locations. The Kruskal-Wallis Method, which can be considered a non-parametric one-way ANOVA, was used to conduct statistical analyses among tests with more than two subgroups. Analyses with only two subgroups utilized the non-parametric Wilcox rank test. Table 3 presents eight cases tested in order to isolate treatment (i.e. factors changed between test trials) effects on weight changes. Pairwise (i.e. ad-hoc) comparisons were done to complement the Kruskal-Wallis test results.

The test results presented in Table 3 varied greatly in terms of rejection or acceptance of the null hypothesis. While cases 2 – 5 resulted in statistical confirmation of the initial hypothesis that similar test conditions produced no significant differences in weight changes within a 5% confidence, other cases appear to contradict that hypothesis. For example, in case 8 where the treatments were identical, the resulting p-value states that the weight changes between Tests 2.3 and

2.4 were statistically different. However, due to high variability between test trials (i.e. multiple treatments in an experiment), reliable conclusions from the second set of comparative tests cannot be made in this study.

Table 3. Comparison of data between experiments with similar treatments

Case	Stat ID	Treatment Varied	Statistical Test	Test Score	p-value
1	1.1, 1.2, 1.3	Unprotected module location	Kruskal-Wallis	6.03	.05*
2	1.1, 1.4	Module depth, unprotected module location	Wilcox	42	.93
3	1.4, 1.5, 1.6	Unprotected module location	Kruskal-Wallis	0.27	.88
4	2.1, 2.2	Plant types, test duration (2.2)	Wilcox	57.5	.14
5	2.2, 2.5	Module depth	Wilcox	26.5	.23
6	2.3, 2.4, 2.5, 2.6	Plant types, test duration (2.5)	Kruskal-Wallis	13.3	.004*
7	2.3, 2.4, 2.6	Plant types	Kruskal-Wallis	15.7	.0004*
8	2.3, 2.4	None	Wilcox	78.5	.001*

*Null hypothesis rejected

CONCLUSION

This paper presented an analysis of wind resistance of modular tray green roof systems tested on a model building. The methods were presented, and related trends and statistical comparisons were given which explored the effects that different factors have on the growth media scour performance. It was shown that the usage of vegetation and its resulting coverage ratio promotes more erosion control, and minimizes excessive weight changes in modular tray specimens. Further, the usage of a 300 mm tall parapet reduced growth media scour in specimens located along the windward wall, but also produced adverse wind flow conditions that were detrimental to the scour performance of modules located along the leeward wall. Overall, vegetation type and coverage, test duration, and wind direction significantly affect growth media scour. However, the statistical significance of scour-induced specimen weight losses and gains appears more dependent upon the containment of the total growth media on the roof and its limited net weight change during testing, than the successful scour resistance of individual specimen. The high variability between test trials prevented reliable results to be made from the statistical tests conducted between test trials. To better understand the growth media scour resistance of modular tray green roof systems, further studies are needed that utilize larger roofs and more modular tray specimens, limit the treatments varied, and test wind flows that exhibit natural wind characteristics.

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