DRC Deer Ridge Consulting, Inc.

505 Deer Ridge Lane
Ararat, VA 24053
Office: 276-755-9162
Fax: 866-441-1054
www.deer-ridge-consulting.com

Field Investigation of Aggregate Blow-off of Spray Polyurethane Foam Roofs

By
Roger V. Morrison, PE, RRC
Deer Ridge Consulting, Inc.

Presented at the RICOWI Fall Symposium, November 11, 2010, Rock Hill, SC

Abstract

The 2006 International Building Code disallows the use of loose-laid aggregate on roofs in hurricane-prone regions for fear of damage caused by blow-off. This restriction has had a significant impact on the roofing industry as loose-laid aggregate has historically been used as an economic material to increase UV, fire, hail and traffic resistance to roof membranes. In 2009 under the auspices of the Asphalt Roofing Manufacturer's Association, et. al., Jay H. Crandell, P.E. developed a design methodology, based on the 1970s work of Kind and Wardlaw, to avoid aggregate blow-off from roofs of buildings of all heights. As a follow up to the development of this methodology, this researcher has inspected twenty spray-applied polyurethane foam roofs in the Stuart, Florida area that were covered with loose aggregate and subjected to the combined 2004 wind events of hurricanes Francis and Jeanne. Each roof was examined for the variables required in Crandell's Method (i.e., building height, parapet height, aggregate size, wind speed, surface roughness) and the likelihood of aggregate blow-off back calculated to test the methodology; this likelihood was then compared to actual performance.

Background

The use of aggregate as a roof surfacing material has a long track record of providing an economical protective material for resistance to ultra-violet radiation, hail and roof surface traffic. Additionally, aggregate can provide aesthetic qualities and a predator-free nesting place for certain bird species.

However, a well intended but overly restrictive building code change in the 2006 International Building Code (IBC) severely

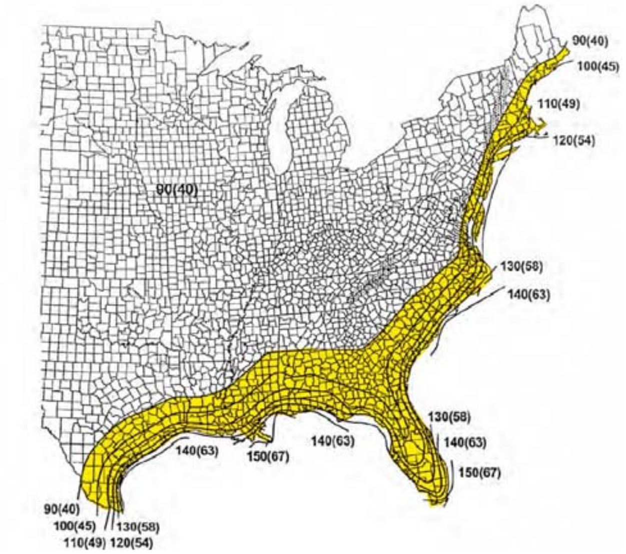

Figure 2: Hurricane-prone regions (Atlantic and Gulf coasts as defined in IBC Section 1609.2.)

restricted the use of loose aggregate as a roof surfacing material in hurricane zones. Specifically:

> **1504.8 Aggregate.** Aggregate used as surfacing for roof coverings and aggregate, gravel or stone used as ballast shall not be used on the roof of a building located in a hurricane-prone region as defined in Section 1609.2, or on any other building with a mean roof height exceeding that permitted by Table 1504.8 based on the exposure category and basic wind speed at the site.

Section 1609.2 defines hurricane-prone regions as:

> **HURRICANE-PRONE REGIONS.** Areas vulnerable to hurricanes defined as:
> 1. The U. S. Atlantic Ocean and Gulf of Mexico coasts where the basic wind speed is greater than 90 mph (40 m/s) and
> 2. Hawaii, Puerto Rico, Guam, Virgin Islands and American Samoa. [Cited here from 2009 IBC.]

Thus, as illustrated in Figure 1, the IBC eliminated a historically economic and reliable roof surfacing material from a substantial geographical segment of the roofing industry.

Beginning in late 2008, the Asphalt Roofing Manufacturers Association (ARMA) sponsored Jay Crandell of ARES Consulting to revisit the wind tunnel work of Canandian researchers Kind and Wardlaw (Kind and Wardlaw, 1976 and 1984). Crandell completed his work in May 2009 and presented his findings at several symposia (Crandell, 2009; Crandell and Fischer, 2010).

Crandell reviewed the Kind-Wardlaw work and developed a modified design method incorporating the effects of parapet height and gravel size. Note that the Kind-Wardlaw work and design methodology was oriented primarily toward avoiding scour on ballasted single-ply roofs whereas the Crandell work focuses on avoiding blow-off. (Crandell's Modified K-W Design Method is reproduced in Appendix A.)

The purpose of this paper is to report the findings of a field study of gravel-covered, spray polyurethane foam roofs which experienced hurricane force winds during hurricanes Francis and Jeanne in 2004.

Introduction

Twenty aggregate-covered, spray polyurethane foam (SPF) roofs at 19 locations (two roofs at one location were combined in the data set) were inspected in the Stuart, Florida area to determine the degree of aggregate blow-off and scouring following the 2004 hurricanes Francis and Jeanne. The physical characteristics of each roof were used to determine the adjusted critical wind speeds (V_{cr}') in accordance with Crandell's Method which were then compared to the estimated actual wind speeds that occurred at the roof (V_{roof}). According to Crandell, roofs where the estimated actual wind speed exceeded the adjusted critical wind speed (i.e., where $V_{cr}' > V_{roof}$) would be at risk for aggregate blow-off.

Determination of Estimated Wind Speeds

Obtaining an accurate analysis of hurricane wind speeds is not a simple task. Hurricane Jeanne was chosen as the more critical storm event (Jeanne was a Category 3 storm, whereas Francis was a Category 2 storm). For this study, wind speeds were estimated using a combination of available Hurricane Jeanne surface wind speed maps and adjusting those speeds to basic wind speeds of three-second gusts at 33 feet above ground, Exposure C. The net result is the wind contour map/study area map in Figure 2.

Roof Inspection Procedures

For each roof/building location, the following data were gathered:

- Building name, address, coordinates
- Building height
- Roof dimensions
- Parapet description and dimensions
- Exposure category
- Aggregate sampled
- Wind effects on aggregate
- Inspection photos
- Google Earth overviews

Wind speeds were estimated based on the Figure 2 map for each building location. The aggregate samples were sieved (to determine average diameter) and measured for specific gravity.

The wind effects on the aggregate were based on observations during the inspections and discussions with building owners and the roofing contractor. Effects were classified as No Scour, Minor Scour, Scour, and Gravel Loss.

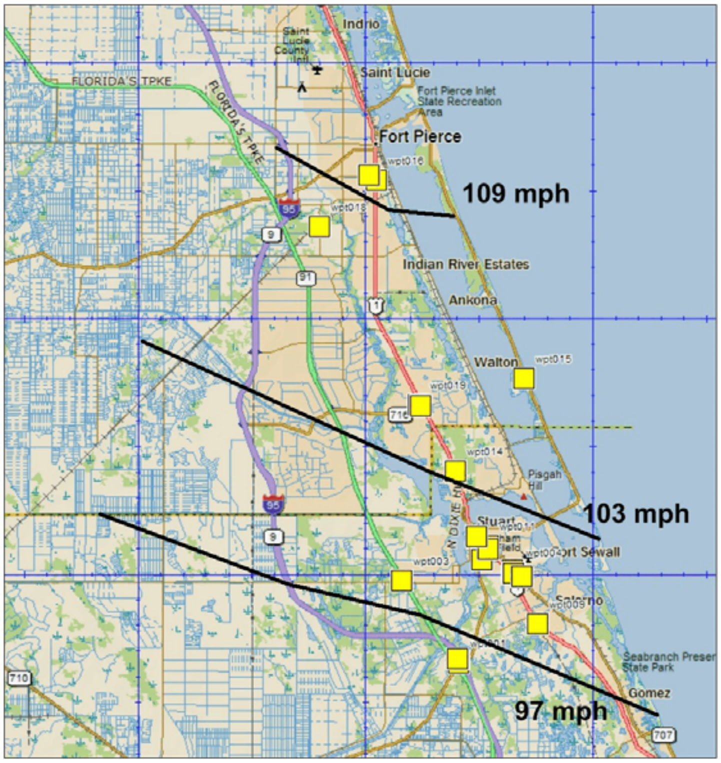

Figure 3: Study area with Hurricane Jeanne wind contours. Yellow squares represent inspected roofs. Wind speeds are 3-second gusts, 33 ft above ground, Exposure C. (Map from Topo North America 9.0; 2010 © DeLorme, Yarmouth, ME. Used with permission.)

Data Analysis

Crandell's Method requires the following data inputs:

V_{map}: The gust speed from the ASCE 7 wind maps. For this study, the estimated wind speeds derived from Figure 2 were used for V_{map} values.

I : The building importance factor for all of the buildings in this study was 1.0 as all of the buildings were classified as Occupancy Category II.

h: The measured building height was used.

h_g: The gradient height for site wind exposure was set at: Exposure B 1270 ft; Exposure C 900 ft. All buildings but one (Roof No. 13 was Exp. C) were Exposure B. Roof No. 14 could be either B or C depending on wind direction, I used Exp. B for the calculations.

α: The power law terrain roughness parameter was set at: Exposure B = 6.2; Exposure C = 9.5.

H: Setting the parapet height for this study presented a dilemma: most of the study building had partial parapets or mixed parapet heights. This is discussed further in the Discussion section of this report. Parapet heights ranged from 0 to 78 inches.

d: Aggregate diameter was determined from sieve analysis of the aggregate samples obtained from the study roofs. Average aggregate diameter varied from 0.245 to 1.5 inches.

Using Crandell's Method, V_{roof} was determined according to Step 2 using the estimated wind speed from the Figure 2 map in place of V_{map}. Next, a critical blow-off wind speed was determined (Crandell's Step 3) based on parapet height. Then, using the measured average aggregate diameter, the adjusted critical speed was determined (V_{cr}'). As a final step (corresponding to Crandell's Step 5), the quantity $(1.1 \times V_{cr}') - V_{roof}$ was calculated (labeled "X-value" for lack of a better designation): the lower the result (the more negative), the likelier aggregate blow-off would occur.

Discussion

Parapet Height

Parapets, partial parapets or porous parapets dramatically affect the wind velocities and pressure differentials across roof surfaces (Canon, et. al., 2002; Phillips, 2003). Many of the study roofs had discontinuous parapets or variable parapet heights. Crandell's Method offers no suggestions regarding mixed parapet heights.

For this study, an "effective" parapet height was used in the calculations. An effective parapet height was defined as the greatest parapet height at the apparent origin of the aggregate scour. This provided the best correlation between observations and Crandell's Method.

For example, Roof No. 2 (Figure 3) drained at the back of the building. The parapet height varied from 10" in front to 36" (due to roof slope) at the rear where the parapet stopped at the draining edge. Aggregate scour originated at the junction of the draining edge and the 36" parapet; an effective parapet height of 36" was used in the calculations for this roof.

Figure 4: Discontinuous parapet on Roof No. 2.

General Findings

X-values (i.e., $1.1xV_{cr}' - V_{roof}$) of the various roofs varied from a low of -52 (aggregate blow-off) to a high of +88 (no scour). Table 3 lists the details of each roof in the study. Of the twenty roofs inspected, the overall observations were:

Table 1: Comparisons of Roof Observations

Observation	Number of Roofs	X-Value Range $[1.1 (V_{cr}')] - V_{roof}$
No Scour	7	-27 to +88
Minor Scour	3	-20 to -14
Scour	9	-22 to +37
Blow-off	1	-52

All structures in this study were less than 30 feet in height, all the roofs were SPF with loose-laid aggregate coverings (there was no embedment of the aggregate). All structures were Occupancy Category II: neither an essential facility nor a substantial hazard (IBC, 2009: Table 1604.5).

No Scour

Some of the roofs exhibiting no scour were completely expected.

- Roof No. 8 (X-value: +39) had a 42-inch parapet wrapping the entire roof structure, providing ample protection to the aggregate.
- Roof No. 19 (X-value: +88) had been a ballasted single-ply; when this had been converted to an aggregate-covered SPF roof, the ballast stone was re-used. This roof had the greatest aggregate diameter of the study roofs (1.5" average). Additionally, while this roof had a draining edge, the 38-inch high parapet wrapped around and protected the corner (see Figure 4).

A few of the no-scour roofs were surprises.

- Roof No. 7 (X-value: -27) would have been expected to exhibit some degree of scour: there were no parapets and the average gravel diameter was 0.268 inches. Why this roof with such a low X-value would have performed as well as it did is not understood. The contractor posited that this particular roof has a gravel stop that tends to slow the drainage: during the hurricane(s) the standing water at the roof perimeters may have absorbed the kinetic energy of the wind protecting the submerged aggregate.

Figure 5: Roof No. 19 with 1.5-inch aggregate and a wrap-around parapet.

Scour and Minor Scour

Roofs experiencing some degree of scour ranged in X-values from -23 to +37. Scour patterns were not unexpected. Exposed corners exhibited the classic "heart-shaped" or "V" pattern; corners with partial or discontinuous parapets exhibited a "tear drop" pattern.

Figure 6: Typical minor scour (Roof No. 16).

Figure 7: Typical scour pattern (Roof No. 4).

Figure 8: Typical scour pattern (Roof No. 2).
Photo courtesy Google Earth.

Aggregate Blow-off

Only one roof in the study was observed or reported to have had a loss of aggregate. This particular building (Roof No. 13) had the smallest aggregate diameter of the study (0.245 inches) and was classified as Exposure C. The roof has a high parapet on the west exposure (66 inches) but the eastern side (exposure was an open field) had no parapet. The aggregate loss apparently caused no damage as it was never determined where it landed (likely in the adjoining field). The X-value for this roof was the most negative of the study at −52.

Figure 9: Roof No. 13 exhibited aggregate loss. Roof had no parapet on the side facing Exposure C. Aggregate loss was from the northern half of this roof. Photo courtesy Google Earth.

Aggregate Characteristics

Samples of aggregate were removed from each of the study roofs. The samples were sieved to determine the size distribution from which average diameters and the size classifications were determined. Size classification are shown in Table 2.

Average diameter varied from 0.245 to 1.50 inches. The largest size was aggregate recycled from a ballasted single-ply roof. The smallest sizes (7, 78 and 8) were locally described as “pea gravel.” Fines were found to be minimal and well within ASTM D 448 specification.

Aggregate was composed of various rock species but the specific gravity was remarkably uniform. Specific gravity averaged 2.59 with a range from 2.40 to 2.72. Variation in specific gravity was insufficient to draw any conclusions as to its effect on scour or blow-off.

Table 2: Measured Aggregate Sizes

ASTM D 448 Size	Number of Roofs
3	1
5	2
67	11
68	2
7	1
78	1
8	2

Figure 10: Aggregate varied in average diameter between < ½ inch and 1½ inch. Most roofs had Size 67 (nominally ½” diameter).

Conclusions

Crandell's Method

The major intent of this study was to determine the validity of Crandell's Modified Kind-Wardlaw Design Method for Buildings of All Heights. All of the inspected structures in this study were less than 30 feet in height; conclusions, therefore, are confined to this height limitation.

An X-value calculation was determined to compare the adjusted critical wind speed (V_{cr}') to the actual estimated wind speed (V_{roof}). Per Crandell's Method, a positive X-value would be "safe" from the standpoint of aggregate blow-off. Indeed, this was consistent with the observations.

In fact, Crandell's Method appears to be quite conservative as twelve of the twenty roofs observed had negative X-values but no observed or reported aggregate blow-off. The single roof that did experience blow-off, had an X-value of -52. While this might suggest that Crandell's Method has a "safety factor" of about 50 mph wind speed, this is only one sample and there were multiple uncertainties in this analysis.

Effects of Parapets and Edge Details

The effect of parapets on the generation of corner wind vortexes is quite profound. It appeared from this study that discontinuous parapets which abruptly stopped at a draining edge had significant effects on vortexes. Several roofs exhibited scour patterns that suggested that corner vortexes, which might otherwise lead to aggregate blow-off, instead were disrupted with aggregate scouring in toward the field of the roof and away from the edge.

Roofs with mixed parapet heights or with discontinuous parapets presented a challenge to model under Crandell's Method. After trying a number of variations on what parapet height to use, this study found best correlation with Crandell's Method using an "effective" parapet height as defined as the greatest parapet height at the apparent origin of scour.

There may be subtle yet significant other factors affecting the likelihood of aggregate blow-off (and scour) including edge details (Lin, et. al., 2008). Roof No. 7 should have experienced aggregate scour to some degree: The theory expressed by the roofing contractor that standing water stabilized the aggregate is speculative, though plausible. It's apparent that the micro environment of the roof corner needs further study.

Acknowledgments

The author gratefully appreciates the support and assistance of NCFI Polyurethanes, Mount Airy, NC and Whiting Construction, Stuart, FL.

Table 3: Roof Inspection Observations and Adjusted Critical Wind Speed (V_{cr}')

Roof Number	ID	City	Avg Gravel Size (in)	Bldg Height (ft)	Parapet Ht Eff (in)	Exposure Category	Est Wind Speed	Vroof	Vcr	Vcr'	1.1*Vcr' - Vroof (X-value)	Experience
1	Treasure Coast Commerce Center	Stuart	0.511	20	35	B	96	68.9	121	96	37	Scour
2	Treasure Coast Commerce Center	Stuart	0.464	20	36	B	96	68.9	122	95	35	Scour
3	Whiting Construction	Palm City	0.508	15	0	B	98	67.2	60	48	-14	Minor Scour
4	B & A Industrial Park Bldg A	Stuart	0.469	21.5	0	B	100	72.6	60	47	-21	Scour
5	B & A Industrial Park Bldg H	Stuart	0.350	16	0	B	100	69.2	60	42	-23	Scour
6	Deggeller Bldg	Stuart	0.496	25	0	B	100	74.4	60	48	-22	Scour
7	Arlington Electric	Stuart	0.268	16	0	B	100	69.2	60	39	-27	No Scour
8	Seacoast National Bank	Stuart	0.482	30	42	B	99	75.9	133	104	39	No Scour
9	Stuart Brake and Auto	Stuart	0.466	15	0	B	101	69.2	60	47	-18	No Scour
10	Don Ramons	Stuart	0.345	10	0	B	101	64.8	60	42	-19	Minor Scour
11	Wayne's Auto Repair	Stuart	0.442	15	0	B	100	68.5	60	46	-18	Scour
12	Mayfair Plaza	Stuart	0.620	25	38	B	101	75.2	126	107	43	No Scour
13	Granada Plaza	Stuart	0.245	14	0	C	103	93.2	60	38	-52	Gravel Loss
14	Island Village	Jensen Bch	0.462	15	2	B	106	72.6	63	49	-19	Scour
15	Rent-a-Center (et al) Strip Mall	Fort Pierce	0.520	14	0	B	110	74.5	60	48	-21	No Scour
16	Virginia Avenue Plaza	Fort Pierce	0.605	15	0	B	110	75.4	60	51	-20	Minor Scour
17	Fort Pierce Business Park	Fort Pierce	0.448	15	15	B	107	73.3	86	66	-1	Scour
18	Town Center	Port St. Lucie	0.458	15	18	B	104	71.3	91	70	6	No Scour
19	Blockbuster Video	Port St. Lucie	1.500	14	38	B	104	70.5	126	144	88	No Scour

Appendix A

Modified K-W Design Method

(Reproduced here with permission from Jay Crandell, ARES Consulting, West River, MD.)

Based on the evaluation in the previous section, the modified K-W design method is presented as follows for aggregate surfaced BUR and SPF:

STEP 1: Determine mapped basic (design) wind speed (mph, gust) for standard conditions (33-foot elevation and flat, open terrain – Exposure C) using the ASCE 7-05 wind map (ASCE 2005)

STEP 2: Adjust mapped wind speed (Step 1) to a design wind speed at roof height using the following equation and terrain roughness parameters:

$$V_{roof} = \{[h/hg]^{(1/\alpha)}/[33/900]^{(1/9.5)}\} \text{ x } V_{map} \text{ x I x } K_d = 1.4 \text{ x } [h/hg]^{(1/\alpha)} \text{ x } V_{map} \text{ x I x } K_d$$

where,

V_{roof} = gust wind speed at roof height (mph)
V_{map} = gust wind speed from ASCE 7 wind map (mph)
I = building importance factor (use 0.75 for Category I buildings; 1.0 for Category II; and 1.1 for Categories III & IV)*
h = building roof height (feet)
h_g = gradient height for site wind exposure (Exp B use 1270 ft; Exp C use 900 ft; Exp D use 700 ft)**
α = power law terrain roughness parameter (Exp B – 6.2; Exp C – 9.5; Exp D – 11.5)**
K_d = 0.9 = wind speed directionality factor consistent with ASCE 7 wind load directionality factor***

*Note: importance factors per ASCE 7-05 have been modified to apply to wind speed in lieu of wind load
**Note: parameters for Exposure B are based on “typical” values per ASCE 7 commentary
***For a discussion of the inclusion of the directionality factor see Kind and Wardlaw, 1976, Appendix A.2.6, page 28.

STEP 3: Determine critical (blow-off) wind speed for roof system design as follows:

$V_{cr} = 20.8\ (H) + 60$

where,

V_{cr} = critical wind speed (mph, gust)
H = parapet height above roof surface (feet)

STEP 4: Adjust critical wind speed (Step 3) for aggregate size when different than 1” nominal diameter as follows:

$V_{cr}' = V_{cr} \times (d)^{1/3}$

where,
V_{cr}' = aggregate size-adjusted critical wind speed (mph, gust)
d = aggregate nominal diameter (inches)
(Nominal aggregate diameter is based on mean aggregate size – see examples below)

ASTM D 1863 Size	Nominal Diameter (in)
#7	3/8*
#67	3/8
#6	½
ASTM D 448 Size**	
#4	1
#24	1 ½
#2	2

*ASTM D1863 #7 aggregate has a mean aggregate size similar to #67 aggregate, but with a maximum aggregate size of ½” instead of ¾”
**ASTM D448 aggregate is not typically specified for BUR and SPF roof systems

STEP 5: Verify that $V_{roof} \leq (1.1 \times V_{cr}')$

If the above design check is not satisfied, increase aggregate size or parapet height and re-evaluate starting at Step 3.
(NOTE: The 1.1 factor is a calibration factor derived and justified in Crandell, 2009)

References

ASTM D 1863 “Standard Specification for Mineral Aggregate Used on Built-up Roofs.” ASTM International, West Conshohocken, PA.

ASTM D 448 “Standard Classification for Sizes of Aggregate for Road and Bridge Construction.” ASTM International, West Conshohocken, PA.

Canon, Richard P., Blake S. Joplin, and S. Thomas Watson. 2002. “SMARF Building Cape Canaveral Air Force Station, Florida: Seven Years Later.” *RCI Interface* (September): 24-36.

Crandell, Jay and Michael Fischer. 2010. “Winds of Change: Resolving Roof Aggregate Blow-Off.” Paper presented at the RCI annual meeting, Orlando, Florida, March 25-30, 2010.

Crandell, Jay H. 2009. “Design of Aggregate Surfaced Roofs to Avoid Aggregate Blow-off: Development of a Modified Kind-Wardlaw Design Method for Buildings of All Heights.” Paper presented at the RICOWI Fall meeting, Portland, Oregon, October 1, 2009.

International Code Council. *2009 International Building Code*. International Code Council: Country Club Hills, IL.

Kind, R. J. and R. L. Wardlaw. 1976. “Design of Rooftops Against Gravel Blow-off.” Ottawa, Ontario: National Research Council Canada.

Kind, R. J., M. G. Savage, and R. L. Wardlaw. 1984. “Further Model Studies of the Wind Resistance of Two Loose-Laid Roof-Insulation Systems (High Rise Buildings).” Ottawa, Ontario: National Research Council Canada.

Lin, J. X., P. R. Montpellier, C. W. Tillman, and W. I. Riker. 2008. “Aerodynamic Devices for Mitigation of Wind Damage Risk.” Paper presented at Advances in Wind and Structures (AWAS) conference, Jeju, Korea, May 29-31, 2008.

Phillips, Mary Katherine. 2003. “Evaluation of Mitigation Measures for Reducing High Suction Pressures on Roof Corners.” M.S. thesis, Clemson University.