

# Field Investigation of AGGREGATE BLOW-OFF OF SPRAY POLYURETHANE FOAM ROOFS

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This paper was originally presented at the RICOWI Fall Symposium, November 11, 2010, in Rock Hill, SC.  
It is published for the first time here, courtesy of RICOWI.

## 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 economical material to increase ultraviolet, fire, hail, and traffic resistance to roof membranes. In 2009, under the auspices of the Asphalt Roofing Manufacturers' Association (ARMA) *et al.*, Jay H. Crandell, PE, 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 20 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

Aggregate as a roof surfacing material has a long track record of providing an economical protective material for resistance to ultraviolet radiation, hail, and 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 restricted the use of loose aggregate as a roof surfacing material in hurricane zones. Specifically, it stated the following:

**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 from the 2009 IBC.]

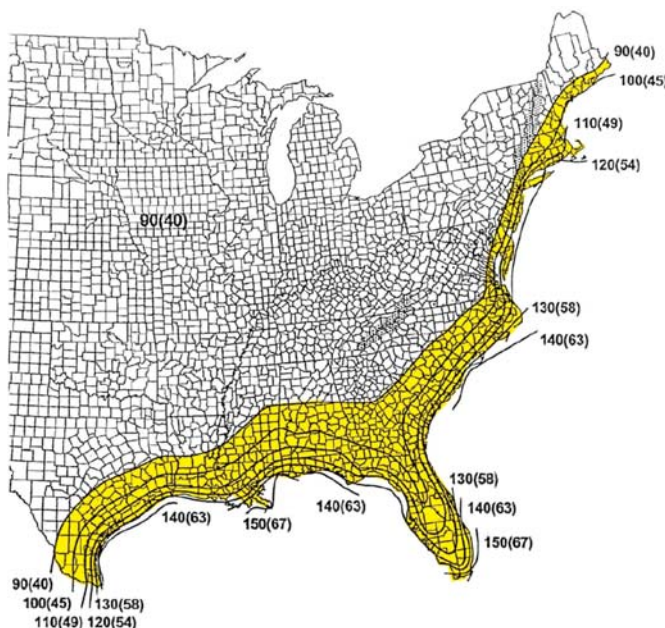


Figure 1 – Hurricane-prone regions (Atlantic and Gulf coasts as defined in IBC Section 1609.2)

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, ARMA sponsored Jay Crandell of ARES Consulting to revisit the wind tunnel work of Canadian researchers 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 were 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 (SPF) roofs that experienced hurricane-force winds during Hurricanes Francis and Jeanne in 2004.

### Introduction

Twenty aggregate-covered, 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. The physical characteristics of each roof were used to determine the adjusted critical wind speeds ( $V_{cr}'$ ) in accordance with Crandell's Method; these 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 ft (10 m) 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.

### 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



Figure 2 – Study area with Hurricane Jeanne wind contours. Yellow squares represent inspected roofs. Wind speeds are three-second gusts, 33 ft above ground, Exposure C. (Map from Topo North America 9.0, 2010, © DeLorme, Yarmouth, ME. Used with permission.)

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 but one building were Exposure B (Roof No. 13 was Exp. C). Roof No. 14 could be either B or C, depending on wind direction; Exp. B was used for the calculations.
- $\alpha$ : The power law terrain roughness parameter was set at Exposure B = 6.2; Exposure C = 9.5.

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**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 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 more likely 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.



*Figure 3 – Discontinuous parapet on Roof No. 2.*



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Roof #	ID	City	Avg. Gravel Size (in)	Building Height (ft)	Parapet Ht. Eff. (in)	Exposure Category	Est. Wind Speed	V <sub>roof</sub>	V <sub>cr</sub>	V <sub>cr</sub> '	1.1 x V <sub>cr</sub> ' - V <sub>roof</sub> (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 Building A	Stuart	0.469	21.5	0	B	100	72.6	60	47	-21	Scour
5	B & A Industrial Park Building H	Stuart	0.350	16	0	B	100	69.2	60	42	-23	Scour
6	Deggeller Building	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 Ramon's	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

Table 1 – Roof inspection observations and adjusted critical wind speed (V<sub>cr</sub>).

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 inches in front to 36 inches (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-in parapet; an effective parapet height of 36 inches was used in the calculations for this roof.

### General Findings

X-values (i.e.,  $1.1 \times V_{cr}' - V_{roof}$ ) of the various roofs varied from a low of -52 (aggregate blow-off) to a high of +88 (no scour). Table 1 lists the details of each roof in the

study. Of the twenty roofs inspected, the overall observations are listed in Table 2.

All structures in this study were less than 30 ft in height, and 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-in parapet wrapping the entire roof

Observation	Number of Roofs	X-Value Range [1.1 (V <sub>cr</sub> ') - V <sub>roof</sub> ]
No Scour	7	-27 to +88
Minor Scour	3	-20 to -14
Scour	9	-22 to +37
Blow-off	1	-52

Table 2 – Comparisons of roof observations.

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 reused. This roof had the greatest aggregate diameter of the study roofs (1.5 inch average). Additionally, while this roof had a draining edge, the 38-in-high parapet



Figure 4 – Roof No. 19 with 1.5-in aggregate and a wrap-around 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 in. 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.

### 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 “teardrop” pattern. (See Photos 5 to 7.)



Figure 5 – Typical minor scour (Roof No. 16).

### 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 in) and was classified as Exposure C (Figure 8). 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.

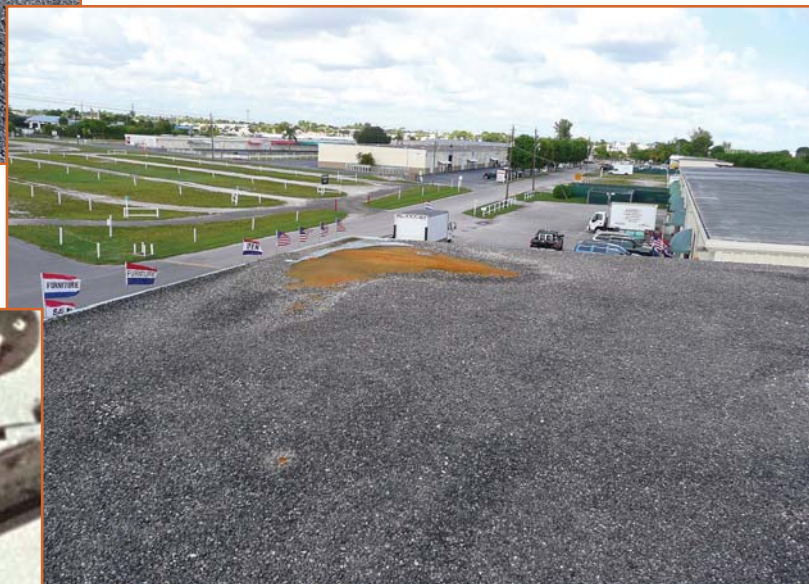


Figure 6 – Typical scour pattern (Roof No. 4).



Figure 7 – Typical scour pattern (Roof No. 2).  
Photo courtesy Google Earth.



Figure 8 – Roof No. 13 exhibited aggregate loss. The 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 classifications are shown in *Table 3*.

Average diameter varied from 0.245 to 1.50 in (*Photo 9*). 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 D448 specification.

Aggregate was composed of various mineral 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.

### 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

ASTM D448 Size	Number of Roofs
3	1
5	2
67	11
68	2
7	1
78	1
8	2

Table 3 – Measured aggregate sizes.



Figure 9 – Aggregate varied in average diameter between less than one-half inch and 1½ inches. Most roofs had Size 67 (nominally one-half-inch diameter).

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of All Heights. All of the inspected structures in this study were less than 30 ft high; 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 since 12 of the 20 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 vortices is quite profound. It appeared from this study that discontinuous parapets that abruptly stopped at a draining edge had significant effects on vortices. Several roofs exhibited scour patterns that suggested that corner vortices, 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 other subtle yet significant 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 microenvironment of the roof corner needs further study. 

### ACKNOWLEDGEMENTS

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

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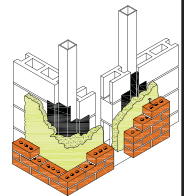
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# APPENDIX A

## MODIFIED K-W DESIGN METHOD

(Reproduced 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-ft 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:

$$V_{\text{roof}} = \left\{ \left[ \frac{h}{h_g} \right]^{(1/\alpha)} / \left[ \frac{33}{900} \right]^{(1/9.5)} \right\} \times V_{\text{map}} \cdot I \times K_d$$

$$= 1.4 \times \left[ \frac{h}{h_g} \right]^{(1/\alpha)} \times V_{\text{map}} \times I \times K_d$$

where,

- $V_{\text{roof}}$  = gust wind speed at roof height (mph).
- $V_{\text{map}}$  = 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 and IV).\*
- $h$  = building roof height (ft).
- $h_g$  = gradient height for site wind exposure (Exp. B use 1270 ft; Exp. C use 900 ft; Exp. D use 700 ft).\*\*
- $\alpha$  = 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.\*\*\*

\*Importance factors per ASCE 7-05 have been modified to apply to wind speed in lieu of wind load.

\*\*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:

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

where,

- $V_{\text{cr}}$  = 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-in nominal diameter as follows:

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

where,

- $V_{\text{cr}}'$  = 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 D1863 Size	Nominal Diameter (in)
#7	3/8*
#67	3/8
#6	1/2
ASTM D448 Size**	
#4	1
#24	1 1/2
#2	2

\*ASTM D1863 #7 aggregate has a mean size similar to #67 aggregate, but with a maximum aggregate size of 1/2 in instead of 3/8 in.

\*\*ASTM D448 aggregate is not typically specified for BUR and SPF roof systems.

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

If the above design check is not satisfied, increase aggregate size or parapet height and reevaluate starting at Step 3.

(Note: The 1.1 factor is a calibration factor derived and justified in Crandell, 2009.)

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