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Ponding and Blisters – Study of SPF roofs

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Multiple roofing systems in the construction industry and installing high-quality roofing products are vital for efficient building operations. Inadequacies in design, materials, installation workmanship or maintenance can result in defects and surface anomalies in the roofing membrane-like blisters, open seams, and holes. The current study investigates if there is a relationship between roof distress features - blisters and ponding and the low slope sprayed polyurethane foam (SPF) roofs, especially when roofs do not conform to the minimum slope of 1/4 inch. The researchers' team conducted a quality inspection survey for the SPF roofs (#96 non-granular and #1068 granular aggregate roofs). The visual observations populated data to develop an account of the percentage of blisters and surface defects such as ponding, penetrations, delamination, and bird pecks of the SPF roofs. Statistical analyses utilizing Pearson correlation, t-test, and Chi-Square test evaluated the correlation between ponding and blisters to confirm if non-conforming roof slopes lead to defects and surface anomalies. As a result, the study established that the roof's slope significantly influenced the ponding area of granular and non-granular aggregate SPF roofs. Ponding and blisters are likely to exist in non-granular while ponding in granular roofs.
Key Words: ponding, blisters, SPF roof, granular aggregate roof, non-granular aggregate roof.

Introduction

The construction industry comprises multiple divisions: roofing, painting, mechanical, masonry, and electrical. Thermal and moisture protection, identification of quality issues, and compliance with quality standards are critical parameters for the ultimate product in all divisions (Gajjar et al., 2015). The roofing sector is critical, with the roof's function being the protection and shelter of the building from the weather (Kalamees et al., 2020; Guyer, 2018). There are multiple roofing systems in the construction industry, and installing high-quality roofing products is vital for efficient building operations (Gajjar et al., 2015). The single-ply roofing system is a system in which the principal roof covering is a single-layer flexible thermoset or thermoplastic membrane. In contrast, the multi-ply roofing system combines traditional materials such as felts and base sheet components. A built-up roof is a continuous, semi-flexible roof membrane consisting of multiple plies of saturated felts, coated felts, fabrics, or mats assembled in place with alternate layers of bitumen and surfaced with

mineral aggregate, bituminous materials, a liquid-applied coating, or a granule-surfaced cap sheet (National Roofing Contractors Association, 2022; Guyer, 2018).

The focus of this study is to evaluate the distress features observed in roof types known as sprayed polyurethane foam (SPF). The SPF-based roof system is a composition of two components; the first is the rigid, closed-cell SPF insulation. SPF is a foamed plastic material formed by mixing and spraying two components—isocyanate ("A-component") and resin containing a polyol ("B-component") to form a rigid, fully adhered, water-resistant, insulating membrane (National Roofing Contractors Association, 2022). The second component is the protective surface, typically a spray-applied elastomeric coating that can be applied using hand and power rollers (Gajjar et al., 2015). SPF is a lightweight, renewable roofing system with excellent insulating performance and can be installed over existing built-up roofing systems. However, the SPF roofing system's performance depends on the accurate and technically competent installation of the two-component system; thus, its performance depends on the contractor's expertise (Kashiwagi et al., 2002, 2016, 2017). 80% of building construction and facility problems pertain to roofing and waterproofing (Gajjar et al., 2014a). Previous research has indicated that inadequacy in design, materials, installation workmanship or maintenance can result in defects and surface anomalies in the roofing membrane-like blisters, open seams, and holes (Bailey & Bradford, 2005). Accumulating water on the roof of the building results in loads and deflections mutually dependent on each other, and the consequence is a non-linear effect known as ponding (Denavit, 2019). Penetration is a construction component (e.g., pipes, conduits, HVAC supports) that passes through a roof or waterproofing system (National Roofing Contractors Association, 2022). Not many studies utilize absolute metrics to measure the performance of a building or facility, and these common areas of measurement include cost, schedule, quality, and safety (Sharma et al., 2021). Quality and overall performance monitoring through regular data collection are critical and visual inspection is one of the methods to achieve it (Gajjar et al., 2014b, 2015). This paper analyzes a dataset of the visually recorded presence of blisters and ponding on low-slope SPF roofs across multiple projects. The study's objective is to evaluate and assess if there is any significant relationship between roof distress features like blisters and ponding with the roof's slope conforming to the minimum value of 1/4 inch.

The study's findings shall assist owners in developing and formulating efficient and effective maintenance plans for roofing systems in the facilities. The basis of the formulation of plans would be the study's findings pertinent to the correlation of the slope of the roofs. The research intends to assist the contractors in a comprehensive understanding of SPF roofs and the technical competence required for their successful and effective installation. The contractors will be further informed about the possible defects that will follow with poor workmanship in non-granular and granular aggregate roofs.

Methodology

Researchers conducted a quality inspection survey for the SPF roofs selected for this research. The observations of the visual inspection were recorded instantaneously, populating data to develop an account of the percentage of blisters and surface defects such as ponding, penetrations, delamination, and bird pecks of the SPF roofs. The following data points were measured in person and documented:

- Square footage of blisters
- Square footage of ponding
- Number of penetrations
- Square footage of delamination
- Square footage of bird pecks
- Slope of the roof (if the slope of the roof is less or more than 1/4")

- Type of roof: Non-Granular Aggregate Roof and Granular Aggregate Roof

The researchers conducted data analysis to study and evaluate the relationship between inspection observations: blisters, ponding with each other, and the roof's slope. Blisters and Ponding areas were studied in their absolute values and in categories of severity of Low, Medium (if applicable), and High by calculating the mean value and defining the limit of the severity. The analysis was structured in three phases delineated below:

1. Phase 1 – Evaluation of the impact of the roof's slope on the percentage of blisters and ponding on granular and non-granular aggregate roofs and study the relationship between the abovementioned parameters.
2. Phase 2 – Evaluation of difference in the area of blisters, ponding, and number of penetrations on the roof for two types of slopes of the non-granular aggregate roof
3. Phase 3 – Evaluation of difference in the area of blisters, ponding, and number of penetrations on the roof for two types of slopes of the granular aggregate roof.

Analyses, namely, Pearson correlation, t-test, and Chi-Square test, evaluated the correlation between ponding and blisters and corroborated if non-conforming roof slopes lead to defects and surface anomalies.

Analysis

A summary of the data captured in the survey is highlighted in Table 1 below. Table 1 reflects the averages of observations of areas of ponding and blisters. The measurements were recorded visually for non-granular aggregate and granular aggregate roofs for two conditions: when the roof's slope was less than 1/4" and when the roof's slope was not less than 1/4".

Table 1
Summary of Ponding and Blisters areas for types and slopes of the roof

	Non-Granular Aggregate Roof		**Granular Aggregate Roof**	
Areas (in sq.ft.)	**slope < 1/4”**	**slope not < 1/4”**	**slope < 1/4”**	**slope not < 1/4”**
No. of Samples	35	61	612	456
Ponding Mean	192	121	489	185
Blisters Mean	5	5	17	12
Total Ponding	6,716	7,410	29,9248	84,583
Total Blisters	190	326	10,622	5,577

Phase 1 Analysis: Non-Granular and Granular Aggregate Roofs

Blisters vs. Slope of Roof

Independent Samples T-test was conducted to assess the influence of the slope of the roof in the percentage area of blisters (in sq. ft.) on a sample database of non-granular and granular aggregate SPF roofs, and it was statistically insignificant. A chi-square test of independence examined the relationship between two categories of the area of blisters ("Low" if the percentage of blisters area was less than the average 0.0798% and "High" if the percentage of blisters area was more than the average 0.0798%) and the slope of the roof, and it was statistically insignificant.

Ponding vs. Slope of Roof

Independent Samples T-test was conducted to assess the difference in the percentage of the area of ponding between two types of roofs, roofs with a slope less than 1/4" and roofs with a slope not less than 1/4", and it was statistically insignificant. A chi-square test of independence examined the relationship between two categories of the area of ponding ("Low" if the percentage of ponding area was lower than the average 1.925% and "High" if the percentage of ponding area was more than the average 1.925%) and the slope of the roof, and it was statistically insignificant.

Phase 2 Analysis: Non-Granular Aggregate Roof

Blisters vs. Slope of Roof

To assess the impact of the two types of the slope, i.e., with a roof slope less than 1/4 inch and the other with a roof slope not less than 1/4 inch in the non-granular aggregate roof, on the area of blisters on the roof, an independent samples t-test was conducted using the square footage of "Blisters" as the dependent variable, and this difference was statistically insignificant. A chi-square test of independence examined the relationship between blisters on the non-granular aggregate roof (Low with an area less than equal to 5 sq. ft., High with an area greater than 5 sq. ft.), and slope of the roof - the relationship between these variables was statistically insignificant.

Blisters (Yes and No) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between blisters on the non-granular aggregate roof (Yes if blisters are present and No if there are no blisters) and the slope of the roof (0 for the slope of roof not less than1/4", 1 or slope of the roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2\ (1, N = 100) = 5.983$, $p < 0.05$ exhibiting a significant relationship between the presence of blisters on the non-granular aggregate roof and the roof's slope.

Table 2
Chi-Square test between "Slope of Roof" and "Blisters" in Non-Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	5.983	1	**.014***		
Fisher's Exact Test				.017	.012
N of Valid Cases	100				

** Significance for p < 0.05*

Ponding vs. Slope of Roof

To assess the impact of the two types of slopes in Non-Granular Aggregate Roofs, i.e., with a roof slope of less than 1/4 inch and the other with a roof slope not less than 1/4 inch on the area of Ponding on the roof, an independent samples t-test was conducted using the square footage of "Ponding" as the dependent variable - and this difference was statistically insignificant. A chi-square test of independence examined the relationship between ponding on non-granular aggregate roof (Low for ponding area less than 5 sq. ft., Medium for ponding area more than 5 sq. ft. and less than 100 sq. ft., High for ponding area more than 100 sq. ft.) and slope of roof - the relationship between these variables was statistically insignificant.

Ponding (Yes and No) vs. Slope of Roof: Chi-square Test. A chi-square test of independence

examined the relationship between ponding on non-granular aggregate roof (Yes if ponding area is present and No if ponding area is absent) and slope of roof (0 for slope of roof not less than1/4", 1 or slope of roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 100) = 4.809, $p < 0.05$ exhibiting significant relationship between presence of ponding on non-granular aggregate roof and the slope of the roof.

Table 3

Chi-Square test between "Slope of Roof" and "Ponding" in Non-Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	4.809	1	**.028***		
Fisher's Exact Test				.033	.025
N of Valid Cases	100				

** Significance for p < 0.05*

Blisters vs. Ponding

Pearson's Correlation Test between Blisters and Ponding for Non-Granular Aggregate Roof with Slope less than 1/4 inch. To investigate whether the area of "Ponding" and "Blisters" were linearly related, a Pearson's correlation coefficient (r) between the two variables was calculated, r = 0.796, n = 35, p < .001. This result suggests that the area of "Ponding" in square footage and the area of "Blisters" in square footage were positively correlated. Specifically, as the area of "Ponding" increases, the area of "Blisters" tends to increase and vice versa.

Table 4

Correlation between "Ponding" and "Blisters" areas on Non-Granular Aggregate Roof with Slope less than ¼ inch

		Ponding Sq Ft	Blister Sq Ft
Ponding Sq Ft	Pearson Correlation	1	0.796**
	Sig. (2-tailed)		< 0.001
	N	35	35
Blister Sq Ft	Pearson Correlation	0.796	1
	Sig. (2-tailed)	**< 0.001****	
	N	35	35

*** Correlation is significant at the 0.01 level (2-tailed).*

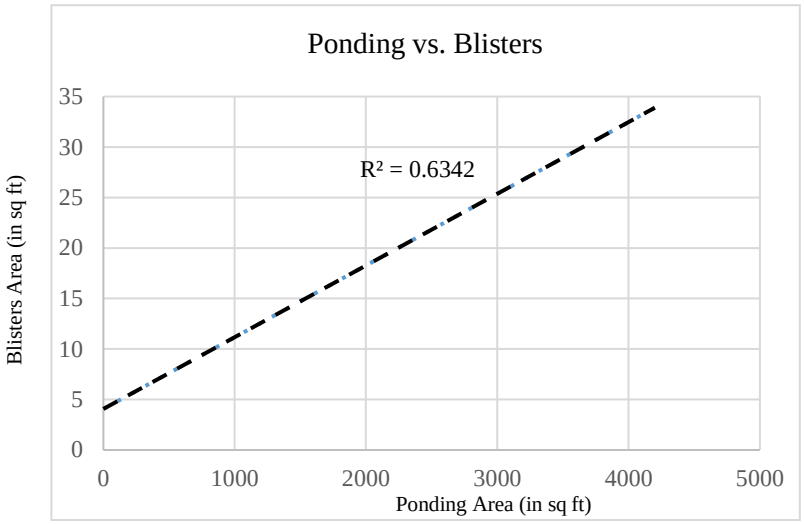

Figure 1. Correlation between ponding & blisters in non-granular aggregate roof (slope less than 1/4")

To investigate whether the area of "Blisters" and the area of "Ponding" were linearly related, a Pearson's correlation coefficient (r) between the two variables was calculated - the result was statistically insignificant. Hence a correlation could not be established between the area of "Blisters" and the area of "Ponding" for non-granular aggregate roofs.

Phase 3 Analysis: Granular Aggregate Roof

Blisters vs. Slope of Roof

To assess the impact of the two types of slopes, i.e. with roof slope less than 1/4 inch and the other with roof slope not less than 1/4 inch in granular aggregate roof, on the area of blisters on the roof, an independent samples t test was conducted using the square footage of "Blisters" as the dependent variable - and this difference was statistically insignificant. A chi-square test of independence examined the relationship between blisters on granular aggregate roof (Low with area less than equal to 15 sq. ft., High with area greater than 15 sq. ft.) and slope of roof. The relationship between these variables was statistically insignificant. A chi-square test of independence examined the relationship between blisters on granular aggregate roof (Yes if blisters are present and No if there are no blisters) and slope of roof. The relationship between these variables was statistically insignificant.

Ponding vs. Slope of Roof

Ponding vs. Slope of Roof: Independent Samples T-test. To assess the impact of the two types of slopes in Granular Aggregate Roofs, i.e., with a roof slope of less than ¼ inch and the other with a roof slope not less than ¼ inch on the area of Ponding on the roof, an independent samples t-test was conducted using the square footage of "Ponding" as the dependent variable. The average impact for a roof with a slope less than ¼ inch (M = 488.97, SD = 2450.97) was greater than that of a roof with a slope not less than ¼ inch (M = 185.48, SD = 1403.81), and this difference was statistically significant, $t(1005.674) = .011$, $p < 0.05$. The 95% confidence interval for the mean difference was (-536.808, -70.164). Overall, it can be deduced that ponding area is higher in granular aggregate roofs with slope less than 1/4 inch.

Table 5
Group Statistics for Independent Samples T-test for "ponding" in granular aggregate roof for two types of slopes

	Slope of Roof	N	Mean	Standard Deviation	Standard Error Mean
Ponding Sq Ft	Slope not less than 1/4"	456	185.48	1403.805	65.739
	Slope less than 1/4"	612	488.97	2450.971	99.075

Table 6
Independent Samples T-test for "ponding" in granular aggregate roof for two types of slopes

		t	df	Two-Sided p	Mean Difference
Ponding Sq Ft	Equal Variances not assumed	-2.552	1005.674	**.011***	-303.486

** Significance for p < 0.05*

Ponding (Low and High) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between ponding on granular aggregate roof (Low for ponding area less than 359 sq. ft., High for ponding area more than 359 sq. ft.) and slope of roof (0 for slope of roof not less than1/4", 1 or slope of roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 1068) = 30.463, p < .001. Results show that ponding is more likely to be present in granular aggregate roofs with slope less than 1/4 inch.

Table 7
Chi-Square test between "Slope of Roof" and "Ponding" in Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	30.463	1	**< .001****		
Fisher's Exact Test				< .001**	< .001**
N of Valid Cases	1068				

*** Significance for p < 0.001*

Ponding (Yes and No) vs. Slope of Roof: Chi-square Test. A chi-square test of independence examined the relationship between ponding on a granular aggregate roof (Yes if ponding area is present and No if ponding area is absent) and slope of the roof (0 for the slope of roof not less than1/4", 1 or slope of the roof less than 1/4"). The relationship between these variables was statistically significant, $\chi 2$ (1, N = 1068) = 25.675, p < 0.001 exhibiting a significant relationship between ponding on the granular aggregate roof and the roof's slope.

Table 8
Chi-Square test between "Slope of Roof" and "Ponding" in Granular Aggregate Roof

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (2-sided)
Pearson Chi-Square	25.675	1	**< .001****		
Fisher's Exact Test				< .001**	< .001**
N of Valid Cases	1068				

*** Significance for p < 0.001*

Blisters vs. Ponding

To investigate whether the area of "Ponding" and "Blisters" were linearly related for Granular Aggregate roofs with slope less than 1/4 inch, a Pearson's correlation coefficient (r) between the two variables was calculated - the result was statistically insignificant. To investigate whether the area of "Ponding" and "Blisters" were linearly related for Granular Aggregate roofs with slope not less than 1/4 inch, a Pearson's correlation coefficient (r) between the two variables was calculated - the result was statistically insignificant. Thus, a correlation could not be established between the area of "Blisters" and the area of "Ponding" for granular aggregate roofs.

Results

The findings from the analyses that exhibited statistically significant results in the three phases are tabulated in Table 9 below.

Table 9
Statistically significant results from Phase I, II, and III analyses

Type of Roof	Independent Variable	Dependent Variable	Statistical Analysis	p-value
Non-granular aggregate roof	Slope of Roof	Yes vs. No for Blisters	Chi-Square	.014*
		Yes vs. No for Ponding	Chi-Square	.028*
Non-Granular Aggregate Roof with Slope < ¼"	Ponding Sq ft and Blisters Sq ft		Pearson's Correlation	< .001**
Granular Aggregate Roof	Slope of Roof	Ponding Sq. ft.	t-test	.011*
	Slope of Roof	Low vs. High Area of Ponding Sq. ft.	Chi-Square	< .001**
	Slope of Roof	Yes vs. No for Ponding	Chi-Square	< .001**

** Significance for p < 0.05*
*** Significance for p < 0.001*

Discussion

The results obtained from the data analysis conducted for the sample of roofing inspection data indicate significant findings for the roofing industry:

1. In non-granular aggregate roofs, there is a higher probability of blisters and ponding for roofs with slopes less than 1/4 inch.
2. In non-granular aggregate roofs, there is a strong correlation between ponding and blisters in roofs with slopes less than 1/4 inch. The result also indicates that approximately 63% of the variance is shared between ponding and blisters for non-granular aggregate roofs with slopes less than 1/4 inch. The two parameters are also directly related to each other, which implies that as the area of ponding increases, the area of blisters also increases and vice versa.
3. Phase 3 Analysis deduced that the slope of the granular aggregate roof has a more substantial impact on the ponding area recorded; however, there was no significant relationship between the presence of blisters on the granular aggregate roof and the slope of the roof.

The study's findings showed that the roof's slope significantly influenced the ponding area of the granular aggregate roofs. There was also a significant correlation between the "low" and "high" percentage of ponding areas and the roof's slope. Reinforcing this, the correlation between the presence of ponding and the slope of the roof was also significant. However, the data analysis could establish no significant relationship between blisters and ponding for granular aggregate roofs.

Conclusion

This study intends to highlight the relationship between roof distress parameters, namely, blisters and ponding, and evaluate the presence and coverage on roofs with the roof's slope. The data analysis findings show that the roof's slope significantly impacts the ponding area recorded in granular aggregate roofs. On the contrary, there was no significant relationship between blisters and the roof slope for the granular aggregate roof. However, in non-granular aggregate roofs, a strong correlation was observed between blisters and ponding. The significant relationship exhibits that since blisters are primarily a consequence of application/installation shortcomings (Gajjar et al., 2015), contractors are recommended to ensure the accurate, technically adequate installation of SPF roofs for non-granular aggregate type to avoid ponding. There is an opportunity to study the presence of blisters and ponding across different regions using the same dataset for roofing projects to assess if a relationship exists between roof exposure to different climatic conditions. The study can be extended for the evaluation of the influence of different seasons and temperatures on the presence of ponding and blisters on the roof. Also, future scope for research exists in studying the presence of blisters and ponding vis-a-vis the roof's age. Evaluation of the number of penetrations corresponding to the roof's age can also be a future research focus.

References

Bailey, D. M., & Bradford, D. (2005). Membrane and Flashing Defects in Low-Slope Roofing : Causes and Effects on Performance. *ASCE JOURNAL OF PERFORMANCE OF CONSTRUCTED FACILITIES*, *19*(August), 234–243. https://doi.org/10.1061/(ASCE)0887-3828(2005)19

Denavit, M. D. (2019). Approximate ponding analysis by amplified first-order analysis. *Engineering Structures*, *197*(July). https://doi.org/10.1016/j.engstruct.2019.109428

Gajjar, D., Kashiwagi, D., Kashiwagi, J., & Sullivan, K. (2014a). Best Value Case Study for Cold Storage Facility in Miami, Florida. *Journal for the Advancement of Performance Information and Value*, *6*(1), 53. https://doi.org/10.37265/japiv.v6i1.71

Gajjar, D., Kashiwagi, J., Kashiwagi, D., & Sullivan, K. (2014b). Maintaining the Quality of Constructed Facilities Using the Performance Information Measurement System: A Three-Year Study on SPF Roofing. International Journal of Facility Management, 5(2).

Gajjar, D., Kashiwagi, D. T., Sullivan, K. T., & Kashiwagi, J. (2015). Postoccupancy Performance Evaluation of Time-of-Installation Factors: Seven-Year Study of SPF Roofing. *Journal of Performance of Constructed Facilities*, *29*(2), 1–8. https://doi.org/10.1061/(asce)cf.1943-5509.0000500

Guyer, J. P., & PE, R. (Eds.). (2018). An Introduction to Roofing Systems. Guyer Partners.

Kalamees, T., Ilomets, S., Põldaru, M., Klõseiko, P., Kallavus, U., Rosenberg, M., & Õiger, K. (2020). Analysis of causes of the end of service life of a spray polyurethane foam and polyurea roof. *E3S Web of Conferences*, *15002*(172), 1–6. https://doi.org/http://doi.org/10.1051/e3sconf/20201721 0502

Kashiwagi, D. T., & Tisthammer, T. (2002). Information based delivery system for sprayed polyurethane foam in roofing. Journal of Thermal Envelope and Building Science, 26(1), 33-52.

Kashiwagi, D., Zulanas IV, C., & Gajjar, D. (2016). The Cost Effectiveness of Alpha SPF Roofs: Casa View Elementary School Roofing Case Study. Journal for the Advancement of Performance Information and Value, 8(2), 42-57.

Kashiwagi, D. T., Zulanas, C., & Gajjar, D. (2017). The Value of Alpha SPF Roofing: An Alpha Case Study at William Lipscomb Elementary School. *Journal for the Advancement of Performance Information and Value*, *9*(2), 21–48. https://doi.org/10.1044/leader.ppl.22122017.24

National Roofing Contractors Association. (n.d.). *www.nrca.net*. Retrieved October 19, 2022, from https://www.nrca.net/

Sharma, V., Caldas, C. H., & Mulva, S. P. (2021). Development of metrics and an external benchmarking program for healthcare facilities. *International Journal of Construction Management*, *21*(6), 615–630. https://doi.org/10.1080/15623599.2019.1573490