Post Occupancy Performance Evaluation of “Time of Installation” Factors - A Seven Year Study of SPF Roofing

by

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ABSTRACT

Over the past couple of decades, quality has been an area of increased focus. Multiple models and approaches have been proposed to measure the quality in the construction industry. This paper focuses on determining the quality of one of the types of roofing systems used in the construction industry, i.e. Sprayed Polyurethane Foam Roofs (SPF roofs). Thirty seven urethane coated SPF roofs that were installed in 2005 / 2006 were visually inspected to measure the percentage of blisters and repairs three times over a period of 4 year, 6 year and 7 year marks. A repairing criteria was established after a 6 year mark based on the data that were reported to contractors as vulnerable roofs. Furthermore, the relation between four possible contributing time of installation factors i.e. contractor, demographics, season, and difficulty (number of penetrations and size of the roof in square feet) that could affect the quality of the roof was determined. Demographics and difficulty did not affect the quality of the roofs whereas the contractor and the season when the roof was installed did affect the quality of the roofs.

DEDICATION

I would like to dedicate this thesis to Performance Based Studies Research Group (PBSRG) – Del E. Webb School of Construction that has given me the opportunity to work in the construction research field that I have found to be interesting and educational. Through research, PBSRG has given me a more realistic view of the current challenges faced in the construction industry and has equipped me with the necessary skills needed to be successful in the industry. I have had the pleasure to work and collaborate with other outstanding researchers from other disciplines and have different perspectives and outlook.

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Chapter 1

INTRODUCTION

Quality has been a subject of interest in the production and delivery of services for approximately two decades (Lewis, 1993). The term quality is defined differently by different services and there is no consensus on any one specific definition of quality (Wicks and Roethlein, 2009; Sower and Fair, 2005). Reaching a common definition of quality between owners and contractors is critical in order to achieve the desired expected quality since a building's service life is directly impacted by quality (Newton & Christian 2006; Zbranek, 2000). There are multiple researchers that define and study various ways on achieving quality using different quality methods.

One such method of construction quality can ultimately be achieved through the setting of specific performance standards and processes (Horowitz, 2001). Quality of the materials used in the construction is also an important element, which can be achieved through planning, prevention, appraisal and specific corrective actions (Stukhart, 1989). The efforts that the contractor and engineers put in to produce a finished product, based on contract plans, specifications and meeting customer satisfaction requirements, can also be defined as quality (Hart 2005; Flynn et. al. 1994; Burati et al. 1991). Newton and Christian (2006) and Garcez et. al. (2013) also suggests that the quality of a building can be influenced in the initial design phase. The total quality management (TQM), supply chain and their partnering methods are currently being used in the construction industry to solve the problem of low or poor quality. However, these methods yield the desired result only with the creation of quality culture for different parties to operate in (Gopal &

Wong, 1998). Vecchi & Brenna (2009) uses national culture to identify differences in quality management.

Other quality methods such as lean production and six sigma have found success in the manufacturing market, but they have been unable to find a niche in the construction industry, creating ambiguity (Sullivan, 2011; Tam et. al., 2008). ISO 9000, a guideline to establishing a new quality system or altering the existing system to meet the requirements, has been applied in the construction industry throughout past decade as a desirable quality measurement system (Low & Hennie, 1997). Performance measurement itself has been given a lot of attention in the past fifteen years in terms of research (Bassioni et. al. 2004; Yang et. al., 2010). One suggestion that has been made is that a quality-measurement matrix should be executed for quality performance measurements in the construction industry (Stevens et. al. 1994). The leadership model in the organization is also seen as one of the key successes to achieving quality. Also, leadership in the organization needs to be strong and committed in order to implement a successful quality process (Shiramizu & Singh, 2007). Kuprenas (2008) has used total project cost (design, management, inspection, testing) to measure the construction quality.

Some researchers have suggested measuring quality and implementing quality methods during the post-construction phase. The Post Occupancy Evaluation (POE) method, where a finished product is evaluated to measure the quality for continuous improvement on future products, is currently being implemented in the industry (Wicks and Roethlein, 2009). Also to measure quality, owner satisfaction questionnaires have been distributed after each project to impact future projects positively through corrective behavior modifications (Forbes 2002; Gajjar et. al. 2012). Inspections also are crucial in the occupancy stages after the construction has been completed to find the latent defects that were not visible during the inspection in the construction phase (Chong & Low 2005). Measurement of the effectiveness of Quality Assurance systems are being used to improve quality in the construction industry (Ahmed et. al. 1998). The Key Performance Indicator (KPI) is another quality measurement method where all stakeholders, including clients, facilitators, and other participants take part in the measurement process as performance indicators (Lin et. al. 2011; Lavy, 2011).

The construction industry consists of many different sub-categories like roofing, painting, mechanical, electrical, masonry, thermal and moisture protection, etc. and identification and maintenance of quality in all sub-categories is crucial for a final quality product. Focusing on the roofing sector, there are many types of roofing systems currently in the construction industry and installation of a quality roofing product is essential for smooth functioning of the building.

This paper focuses on the one of the roofing sectors in the construction industry known as Sprayed Polyurethane Foam (SPF). SPF-based roof systems are constructed by mixing and spraying a two-component liquid that forms the base of an adhered roof system. The first component of an SPF-based roof system is rigid, closed cell, spray polyurethane foam insulation. The second component, the protective surfacing, typically is a spray applied elastomeric coating, though hand and power rollers can be used (www.nrca.net). SPF roofing has an R-value of six per inch and is used by the owners of the building as a recover system over existing roofs including built-up roof, modified bitumen, concrete, wood, asphalt shingles, clay tile, and metal (Knowles, 2005). The effective service life of an SPF product, as per Dr. Rene Dupuis of the National Roofing Foundation, is up to thirty years.

Studies have been conducted to evaluate the long-term weathering effects of performance of SPF roofs to determine energy savings, dynamics of heat transfer and the long-term degradation (Alumbaugh et. al 1984). Studying the causes and effects of SPF roofing defects have revealed that the main reason for these poor results are design, materials, surface anomalies, installation workmanship and overall maintenance that lead to leaking, blistering, open holes and shortened service life (Bailey & Bradford 2005).

Some of the installation challenges for SPF roofing include cleanup if foam is not sprayed correctly, moisture content and installation errors. SPF roofing needs specialized equipment that includes a high pressure gun that shoots liquid foam which quickly hardens as it is exposed to air. If the liquid foam is sprayed in the cavities between walls and ceilings, it is a challenge to cleanup. Trapping of moisture due to open-cell spray foam when insulating roofs can result in rot and mold problems. During installation, handling spray foam could be a challenge due to expansion of spray insulation as it dries that can cause the walls to buckle and crack (Solomon, 2011).

Owners are buying SPF roofing products by relying on long-term warranties that have inclusions that protect the manufacturer and has no correlation to the proven documented performance of the capability of the contractors and the product (Kashiwagi 2011). In order to monitor quality and overall performance, regular data collection is crucial (Tam et. al 2008). One such method is visual inspection and condition assessment procedures that provide data to determine roof performance (Bailey & Bradford 2005; Coffelt et. al. 2010). Evaluating roof coverings using physical inspection and reporting the repair or replacement conditions to the owner have been used for asphalt composition shingles, wood shingles and shakes, and slate and clay tile roofs (Sharara et. al. 2009).

Instead of using performance information, the roofing industry uses specifications to ensure optimal quality of the final product which is not a good approach. This paper presents an analysis of the effects on the quality of SPF roofs over time based upon the installing contractor, season of installation, difficulty (number of penetrations and size of the roof), and local demographics at the buildings' locations by measuring the percentage of blisters on 37 roofs over a three year period of 4, 6, and 7 year increments through visual inspection that can potentially be added to roofing specifications before bidding the job. The cost information (installation and maintenance) for the roofing projects was not well documented and thus was not available to the authors. Cost in relation to quality has unfortunately been omitted from this study.

Chapter 2

METHODOLOGY

One building owner that has been using SPF roof for approximately 10 years was selected for this specific research. The building owner is a large, urban school district in a high-hail fall region of the United States. A measurement structure was implemented to measure the performance of SPF roofs installed in 2005 and 2006. A quality inspection was conducted three times over a period of 4 year, 6 year and 7 year periods for each roof. In 2011, the repairing criteria were identified based on the 4 year and 6 year measurement.

Identifying roofing projects for inspection:

The contractors that installed the SPF roofing for a subject building owner are part of a high performance roofing program. The program is established only for SPF roofing contractors by a coating manufacturer that qualifies and disqualifies contractors based on performance measurements using end user satisfaction ratings. The requirements of the program are:

1. Have a “good financial standing” and “be licensed” with the manufacturer
2. Roof inspections once every two years of a minimum of 25 roofs by a third-party inspector
3. Annual submission of newly installed SPF roofs over 5,000 SF
4. 98% of roofs being tracked cannot currently leak
5. 98% of surveyed roofs must have satisfied customers
6. The contractors must attend annual educational presentation.

From the annual submission of installed SPF roofs over 5,000 SF, thirty seven urethane coated SPF roofs were identified that were installed in 2005 / 2006 for this research. All the roofs have the same structure and the same system.

Inspection Data Survey:

One of the problems faced by the foam roofing industry is the poor quality of workmanship in SPF roofing (Kashiwagi & Tisthammer 2002). As mentioned, the common causes of blistering and surface defects are application errors. An inspection data survey was used to measure the percentage of blisters and surface defects of the SPF roofs (Appendix A).

Pre-inspection:

Four contractors (Contractor A, Contractor B, Contractor C, and Contractor D) in the high performance roofing program and a client that uses the four contractors were notified prior to conducting the inspections. Three of the contractors agreed to partake in the inspections. The client agreed to help with the efforts in regards to inspections for the fourth contractor. Using mapping software the location of the roofs were identified and optimized for faster and efficient inspections.

Inspection:

The temperature has a direct and crucial effect on blisters. The water that remains in the substrate causes blisters as the system heats in the summer (Jaegermann et. al. 1989). In order to observe the blistering and surfacing defects for SPF roofs the inspections were held by a certified roof inspector in the summers of 2009, 2011 and 2012 during the month of August. Inspection data survey for each roof was filled out immediately on the roof to reduce human error. The inspections were conducted from 8 AM to 5 PM and lasted for one week for all three year inspection marks.

Post-inspection:

Based on the inspection results in 2011, repairing criteria were established and any SPF roof that met the following criteria must be repaired until the end of the warranty:

1. Roofs that have blisters more than 1% of the total roof area
2. Roofs that have open blisters / open cracks
3. Roofs that have a blister size of more than 1 square feet
4. Roofs that have current leaks.

If a contractor refuses to repair the roofs that met the above criteria, the end user will be dissatisfied affecting the high performance roofing program requirement of 98% customers satisfied eliminating the contractor from the program**.**

Chapter 3

ANALYSIS

Repairs:

Based on the criteria, ten roofs and twenty three roofs out of thirty seven roofs were reported as non-performing roofs in 2011 and 2012, respectively (Table 1). No non-performing roofs were reported in 2009 (Fig. 1). After conducting the inspections the respective contractor was notified within one week with the respective non-performing roof. Every job was given a "Y" if it meets the repairing criteria and "N" if it does not meet the repairing criteria as shown in Appendix B. The roofs have to fulfill at least one criterion as a "Y" to be classified as vulnerable.

Criteria 1 - Roofs that have blisters on more than 1% of the total roof area

Criteria 2 - Roofs that have open blisters / open cracks (Fig. 2)

Criteria 3 - Roofs that have a blister size of more than 1 square foot (Fig. 3)

Criteria 4 - Roofs that have current leaks.

The contractors were accountable for their work and fixed all the roofs due to the repairing criteria within 90 days of notification.

Table 1: Vulnerable roofs in 2011 and 2012

Contractor	Vulnerable Roofs - 2011	Repaired Roofs - 2011	Vulnerable Roofs - 2012	Repaired Roofs - 2012	Pending Roofs for Repair
Contractor A	8	8	18	18	0
Contractor B	0	0	0	0	0
Contractor C	0	0	2	2	0
Contractor D	2	2	3	3	0

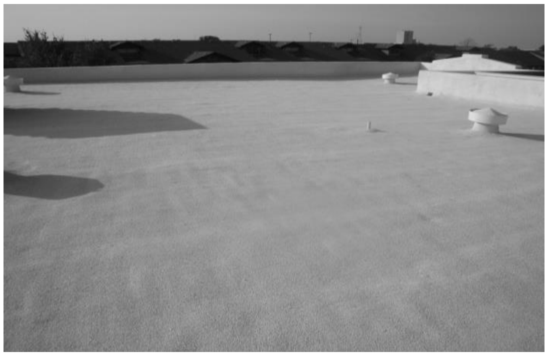

Fig. 1: Non-defective SPF Roof Fig. 2: Defective SPF roof with open cracks

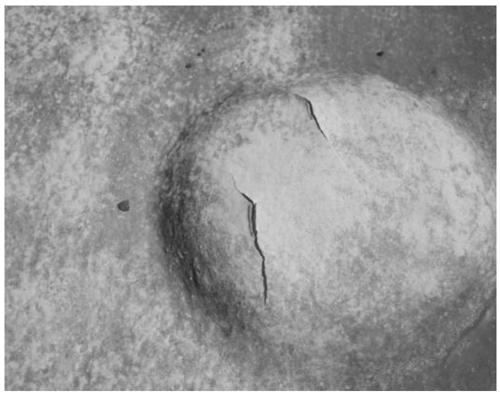

Fig. 3: Defective SPF roof with open blister more than 1 SF

Contractor vs. percent blistered:

In order to determine if the contractor awarded the project has an impact on the quality of SPF roofs, the percentage of blisters for each contractor were measured for each year by dividing the total square feet of blisters each year by the total square feet of the roof area inspected (Table 2). The overall percentage of blisters was calculated by dividing the total square feet of blisters for all three years by the total square feet of the roof area inspected for each contractor (Table 3). Based on the data, the contractor vs. percent blistered for each year was plotted as a bar graph (Fig. 4).

Table 2: Percentage of blisters for each year

Contractor	Percent Blistered 2009	Percent Blistered 2011	Percent Blistered 2012
Contractor A	0.20%	0.12%	0.12%
Contractor B	0.02%	0.00%	0.00%
Contractor C	0.03%	0.05%	0.07%
Contractor D	0.41%	0.35%	0.28%

Table 3: Overall percentage of blisters

Contractor	Overall Percent Blistered
Contractor A	0.44%
Contractor B	0.02%
Contractor C	0.15%
Contractor D	1.04%

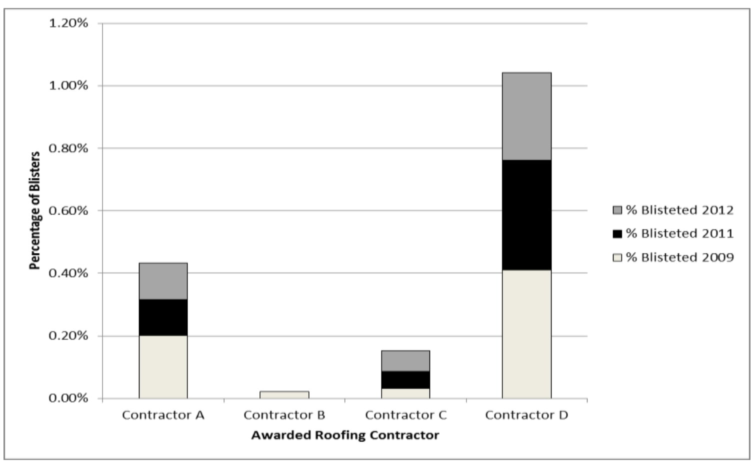

Fig. 4: Percent blistered by year for contractor

From the data, Contractor D has the most percentage of blisters while Contractor B has the least percentage of blisters. Contractor D has 136.7% more percentage of blisters compared to the total average percent blistered of 0.44%. Contractor A has the same percent blistering rate compared to the total average percent blistered, Contractor B has no blisters and Contractor C has significantly less blisters compared to the total average percent blistered. Considering Contractor D in relation to the other contractors, there is a statistically significant difference with a t-statistic of 2.256, significant at the 95% level with a p-value of 0.013.

Season installed vs. percent blistered:

In order to determine if the season the SPF roof was installed has an impact on quality of SPF roofs, the percentage of blisters for each season was determined. The jobs installed in March, April and May were categorized as the Spring season, jobs installed in June, July and August were categorized as the Summer season, jobs installed in September, October and November were categorized as the Fall season and jobs installed in December, January and February were categorized as the Winter season. Overall percent blistered for each season was calculated by dividing the total square feet of blisters for each season by the total roof area for each roof installed for that season (Table 4). Based on the data, a bar graph of season installed vs. overall percent blistered was plotted (Fig. 5).

Table 4: Overall percent blistered by season

Season Installed	Percent Blistered
Spring	0.18%
Summer	0.34%
Fall	0.21%
Winter	0.50%

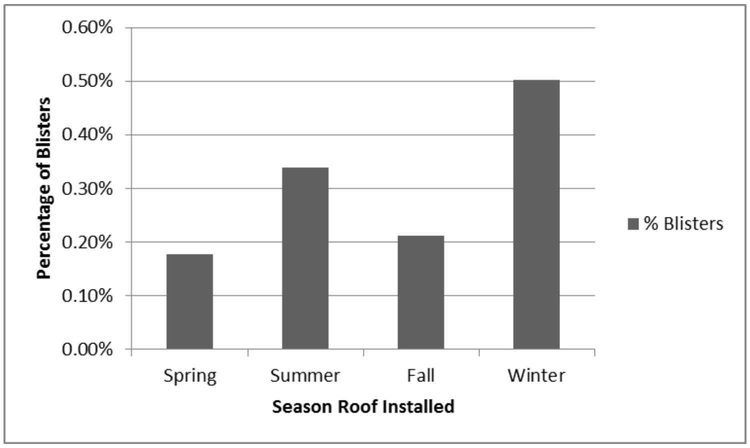

Fig. 5: Percent blistered by season

From the data and the graph, the jobs installed in winter season had most percentage of blisters whereas the jobs installed in Spring season had the least percentage of blisters. The winter season had 13.6% more percent blistered compared to the total average percent blistered of 0.44% per year. The Spring, Summer and Fall season had 59.1%, 22.7% and 52.3% less percentage of blisters compared to the total average percent blistered of 0.44% per year. Considering the Spring and Winter quality levels, there is a statistically significant difference with a t-statistic of 1.792, significant at the 95% level with a p-value of 0.042.

Complexity vs. percent blistered:

The complexity of SPF foam roof is determined based on the roof size (square feet) and the number of penetrations on the roof. Roof penetrations are the various types of vents that allow the movement of gas from the inside of the building to the outside. In order to relate the quality of the SPF roofs to its complexity, the percentage of blisters for each roof were plotted using a scattering plot compared to penetration and square feet of a roof.

All the roofs that have penetrations between zero and two hundred and fifty were plotted (Fig. 6). One job had a penetration of eight hundred which was excluded from the data as an outlier.

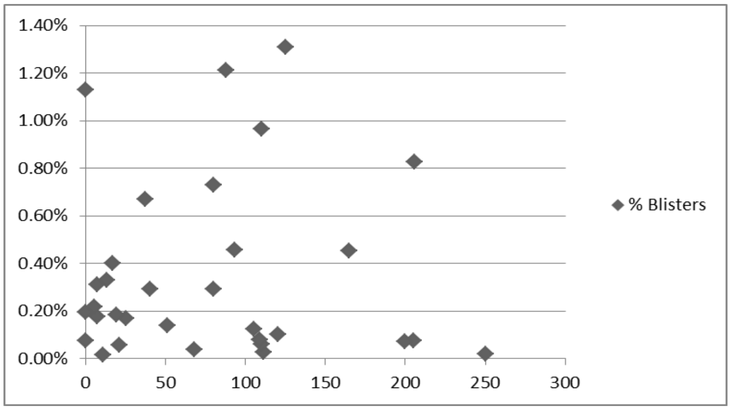

Fig. 6: Percent blistered by penetrations

Based on the scatter plot, there is no relationship between penetrations (#) on the roof to the percentage of blisters on the roof. Furthermore, every job was categorized into five categories based on number of penetrations: 0-50, 51-100, 101-150, 151-200, and 201-250 and the total percentages of blisters for each category were calculated (Table 5). Based on data, a graph of penetration categorizes vs. percent blistered were plotted as shown (Fig. 7).

Table 5: Percent blistered for penetration category

Penetration Category	**Percent Blistered**
0-50	0.29%
51-100	0.46%
101-150	0.18%
151-200	0.25%
201-250	0.35%

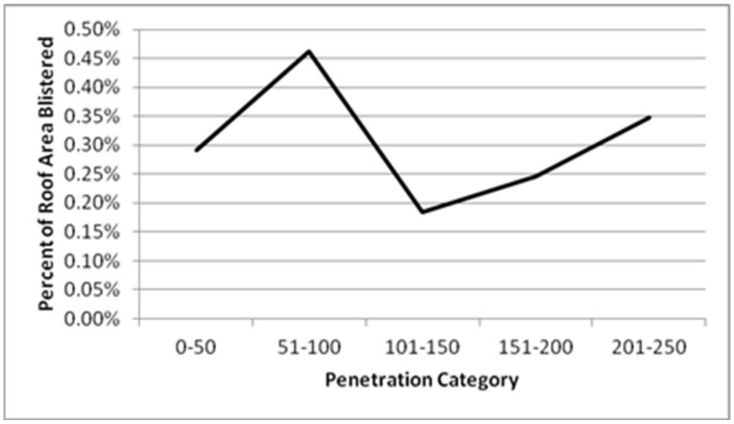

Fig. 7: Percent blistered by penetration category

However, roofs that had penetrations between 101 and 150 had the least percentage of blisters compared to other penetration range whereas penetrations between 51 and 100 had the most percentage of blisters. There is no relationship between the complexities of number of penetrations of the roof to the percentage of blisters on the roof.

Fig. 8 shows the plot of roof size in square feet vs. the percent blistered. There is no relationship between roof size (SF) and percent of roof blistered.

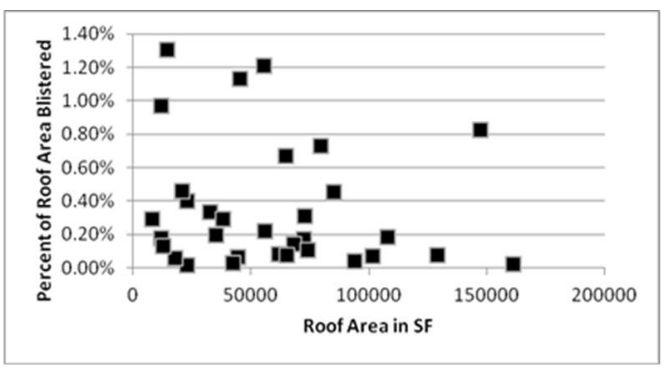

Fig. 8: Percent blistered by roof size (SF)

Demographics (median income) vs. percent blistered:

In order to determine if the affluence of the surroundings impact the quality of SPF roofs, every roofing job was assigned a zip code based on the location of the school. Every school has students enrolled from the nearby areas. The average median income for every zip code was obtained using zip atlas. Using the average income of $32,895, eighteen jobs were categorized as above average where the average median income was above $32,895 and nineteen jobs were categorized as below average where the average median income was below $32,895.

Table 6 shows the percentage of blisters for each category by year. Based on the data, the inspection year vs. percent blistered was plotted as shown in Fig. 9. The jobs that were "above average" location have relatively less percentage of blisters compared to the "below average" location. However, upon performing a t-test, the overall total deviations of the blisters were statistically insignificant with a p-value of 0.13.

Table 6: Percent blistered by year for annual median income

Criteria	**Percent Blistered 2009**	**Percent Blistered 2011**	**Percent Blistered 2012**
Above Average	0.19%	0.10%	0.10%
Below Average	0.20%	0.14%	0.13%

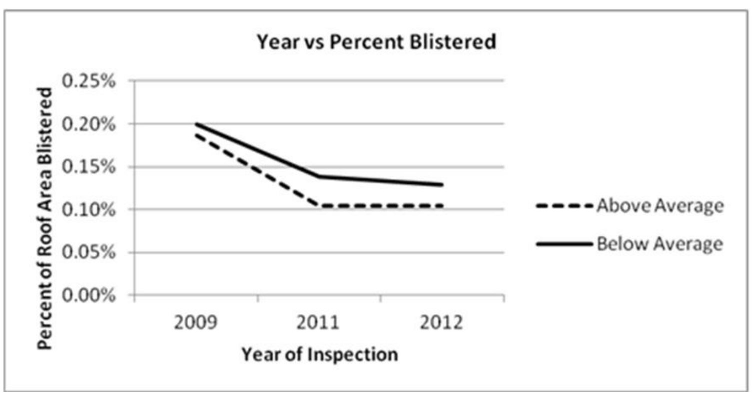

Fig. 9: Percent blistered by average annual median income

Chapter 4

DISCUSSION

In the roofing area of the construction industry, specifications play a major role in achieving the desired project result. Moreover, the roofing industry uses specifications as one of the ways to achieve the desired quality of the roof. Most of the specifications in the roofing industry include the description of quality assurance, delivery, storing and handling of materials, application of the product and cleaning and is directly related to product and installing procedures.

After identifying the effects of quality on a SPF foam roof based on conditions other than material and installation, the season the roof should be installed affected the quality of the SPF roofs. Some specifications mention the project environmental conditions necessary for the application of the product, but the exact time of the year that the product needs to be installed is missing. From the data, the months of May to September are optimal for the installation of SPF roofs. Adding this criterion to the SPF roof specification can help improve the quality of the SPF product due to less moisture in the air, and hence less air trapped in the substrate, resulting in minimal blisters increasing the quality of the SPF roof.

The type of contractor selected affects the end result of an SPF roof. The SPF roofing specification does not have guidelines that are needed to award a roofing contractor. The specification should include the requirement of past performance information on the roofing projects for the contractors bidding. This will provide a client with the past history of the contractor to perform quality work.

The relationship between the quality of an SPF roof to the demographics of the area the roof is installed was studied in order to determine if the surrounding areas and neighborhood affected the contractors perception on the quality while installing the roof. However, there is no causal relationship between mean income of the surrounding community and performance of a roof.

Chapter 5

CONCLUSION

The contractor selected for the installation of the roof affects the quality of SPF roofs. Contractor D had the most percentage of blisters whereas Contractor B had no blisters. The roofing industry relies heavily on the specifications to achieve the desired quality of the SPF roofing system. In spite of the same specifications, the contractors installing the SPF roof had different percentage of blisters after the installation. The authors conclude that along with the specifications the right selection of the contractors is crucial in order to achieve the desired quality of the SPF roofing. This supports the conclusion of Garcez et. al. (2012) that studied ceramic tile roofs and identified the execution errors and maintenance errors were the reasons for the non-performance of ceramic tile roofs. The execution and the maintenance of the roof is the responsibility of the contractor until the end of the warranty.

The quality of SPF roofs is also affected by the season the roof is installed. The roofs that were installed in the winter season have 13.6% more percentage of blisters compared to the average percent blistered, whereas roofs installed in summer, fall and spring have a relatively less percentage of blisters. The installation of SPF roofing should not be conducted in the winter season due to the high moisture content in the atmosphere that can lead to potential failure of the roofing system and cause problems after the installation. Summer season is concluded to be optimal for the installation of SPF roofing system.

The demographics and the difficulty of the roofs did not affect the quality of the roofs. The locations where the roof was installed in the “below average” category where the average median income was below the overall average income of $32,895 had 17.5% more blisters compared to “above average” category. Therefore, it can be concluded that below average household areas have more percentage of blisters on the roofs compared to above average households, but the overall total deviation is insignificant with a p-value of 0.13.

The complexity of the roof in regards to the roof size in square feet and the number of penetrations had no relationship with the percentage of blisters on the roof. Hence, the complexity of the roof did not affect the quality of the SPF roof.

The contractors selected for this research are from the high performance roofing program that is a quality based program that creates accountability among SPF roofing contractors by repairing the roofs until the end of the warranty. The program uses performance measurements using non-technical visual inspections that help contractors, clients and manufacturers by inspecting the existing surface condition on the roof. The end user is satisfied with the contractor in the program leading to a “win-win-win” scenario for contractors, clients and manufacturers due to contractors’ accountability after inspections.

REFERENCES

Ahmed, A. A., Williams, T., Hibberd, P., & Gronow, S. (1998). Measuring the effectiveness of quality assurance systems in the construction industry. *Property Management, 16*(4).

Alumbaugh, R. L., & Humm, E. F. (1984). Experimental Polyurethane Foam Roof Systems. *Journal of Cellular Plastics*, 257-273.

Bailey, D. and Bradford, D. (2005). ”Membrane and Flashing Defects in Low-Slope Roofing: Causes and Effects on Performance.” *J. Perform. Constr. Facil.*, 19(3), 234–243. doi: 10.1061/(ASCE)0887-3828(2005)19:3(234).

Bassioni, H., Price, A., and Hassan, T. (2004). ”Performance Measurement in Construction.” *J. Manage. Eng.*, 20(2), 42–50. doi: 10.1061/(ASCE)0742-597X(2004)20:2(42).

Burati, J. L., Mathews, M. F., and Kalidindi, S. N. (1991). “Quality management in the construction industry.” J. Constr. Eng. Manage.,117(2), 341–359.

Chong, W. and Low, S. (2005). ”Assessment of Defects at Construction and Occupancy Stages.” *J. Perform. Constr. Facil.*, 19(4), 283–289. doi: 10.1061/(ASCE)0887-3828(2005)19:4(283).

Coffelt, D., Hendrickson, C., and Healey, S. (2010). ”Inspection, Condition Assessment, and Management Decisions for Commercial Roof Systems.” *J. Archit. Eng.*, 16(3), 94–99. doi: 10.1061/(ASCE)AE.1943-5568.0000014.

Flynn, B. B., Schroeder, R. G., and Sakakibara, S. (1994). “A framework for quality management research and an associated measurement instrument.” J. Oper. Manage., 11(4), 339–366.

Forbes, L. H. (2002). Continuous Learning in Construction through Quality-Based Post Occupancy Evaluation. *IIE Annual Conference. Proceedings*, 1-7.

Gajjar, D. R., Kashiwagi, D. T., & Kashiwagi, J. (2012). Manufacturer's New Approach To Risk. *RICS COBRA 2012*, 1859-1868.

Garcez, N., Lopes, N., De Brito, J., & Sá, G. (2012). Pathology, diagnosis and repair of pitched roofs with ceramic tiles: Statistical characterisation and lessons learned from inspections. *Construction and Building Materials, 36*, 807-819.

Garcez, N., Lopes, N., De Brito, J., Sá, G., & Silvestre, J. D. (2013). The influence of design on the service life of pitched roofs’ cladding. *ASCE Journal of Performance of Constructed Facilities*.

Gopal, K. K., & Wong, A. (1998). Quality culture in the construction industry. *Total Quality Management*, *9*(4/5), S113-S140.

Hart, J. A. (2005). Construction Quality Management System. *ASQ World Conference on Quality and Improvement Proceedings*, *59*, 353-360.

Horowitz, D. (2001). Construction Quality. *Professional Builder*, *65*(8), 35.
Jaegermann, C., Puterman, M., and Haviv, E. (1989). ”Blistering of Membranes Over Foam-Concrete Roofs.” *J. Mater. Civ. Eng.*, 1(1), 31–45. doi: 10.1061/(ASCE)0899-1561(1989)1:1(31).

Kashiwagi, D. (2011) *PIPS / PIRMS: The Best Value Standard*. 11th ed. Tempe: KSM.

Kashiwagi, D. T. and Tisthammer, T. (2002) Information Based Delivery System for Sprayed Polyurethane Foam on Roofing, *Journal of Thermal Envelope & Building Science*, (26), 33-52.

Knowles, M. (2005, September 29). *Specifying SPF Roofing Systems*. Retrieved April 17, 2013, from http://www.buildings.com/article-details/articleid/2753/title/specifying%20spf%20roofing%20systems.aspx.
Kuprenas, J. A., (2008). Influence of Quality on Construction Costs. AACE International Transactions. (e.g. 2), pp.CSC.05.1 - CSC.05.9.

Lavy, S. (2011). A Literature Review on Measuring Building Performance by Using Key Performance Indicators. *AEI 2011 : Building Integration Solutions*, 406-417.
Lewis, B. R. (1993). Service Quality Measurement. *Business And Economics--Marketing And Purchasing*, *11*(4), 4-12.

Lin, G., Shen, G., Sun, M., and Kelly, J. (2011). ”Identification of Key Performance Indicators for Measuring the Performance of Value Management Studies in Construction.” *J. Constr. Eng. Manage.*, 137(9), 698–706. doi: 10.1061/(ASCE)CO.1943-7862.0000348.

Low, S. P., & Hennie, F. O. (1997). The effective maintenance of quality management systems in the construction industry. *The International Journal of Quality&Reliability Management*, *14*(8), 768-790.

Newton, L. and Christian, J. (2006). ”Impact of Quality on Building Costs.” *J. Infrastruct. Syst.*, 12(4), 199–206. doi: 10.1061/(ASCE)1076-0342(2006)12:4(199).

Sharara, L. M., Jordan, J. W., & Kimble, R. A. (2009). Residential Roofing Evaluation. *Forensic Engineering 2009: Pathology of the Built Environment*, 184-193.

Shiramizu, S., & Singh, A. (2007). Leadership to Improve Quality within an Organization. *Leadership and Management in Engineering*, *7*, 129-140.

Solomon, J. (2011, July 12). Problems with Spray Foam Insulation | Javic Homes Blog [Web log post]. Retrieved from http://javichomes.wordpress.com/2011/07/12/problems-with-spray-foam-insulation.

Sower, V., and Fair, F. 2005. There is more to quality than continuous improvement: Listening to Plato, The Quality Management Journal, 12(1): 8-20. *Spray polyurethane foam-based (SPF) roof systems | NRCA National Roofing Contractors Association*. (n.d.). Retrieved April 17, 2013, from http://www.nrca.net/consumer/types/spf.aspx.

Stevens, J., Glagola, C., and Ledbetter, W. (1994). ”Quality-Measurement Matrix.” *J. Manage. Eng.*, 10(6), 30–35. doi: 10.1061/(ASCE)9742-597X(1994)10:6(30).

Stukhart, G. (1989). ”Construction Materials Quality Management.” *J. Perform. Constr. Facil.*, 3(2), 100–112. doi: 10.1061/(ASCE)0887-3828(1989)3:2(100).

Sullivan, K. (2011). ”Quality Management Programs in the Construction Industry: Best Value Compared with Other Methodologies.” *J. Manage. Eng.*, 27(4), 210–219. doi: 10.1061/(ASCE)ME.1943-5479.0000054.

Tam, V., Le, K., and Le, H. (2008). ”Using Gaussian and Hyperbolic Distributions for Quality Improvement in Construction: Case Study Approach.” *J. Constr. Eng. Manage.*, 134(7), 555–561. doi: 10.1061/(ASCE)0733-9364(2008)134:7(555).

Vecchi, A., & Brennan, L. (2009). Quality management: a cross-cultural perspective. *Cross Cultural Management*, *16*(2), 149-164.

Wicks, A. M., & Roethlein, C. J. (2009). A Satisfaction-Based Definition of Quality. *The Journal of Business and Economic Studies*, *15*(1), 82-97.

Yang, H., John F.Y. Yeung, Albert P.C. Chan, Y.H. Chiang, & Daniel W.M. Chan. (2010). A critical review of performance measurement in construction. Journal of Facilities Management, 8(4), 269-284. doi: 10.1108/14725961011078981.

Zbranek, S. (2000). Quality construction--part 1: Defining quality construction. *Professional Builder*, *65*(8), 77-80.

APPENDIX A

INSPECTION SURVEY

OWNER INFORMATION

User Name			
Building Name		Date Installed	
Street Address	City	State	Zip
Point of Contact	Phone	Area (sq. ft.)	

INPSECTION DATA

Date Inspected	
Is the Roof Slope Less Than ¼" (1 = Yes / 0 = No)	
Does the Roof Have More Than 5% Ponding Water	☐ **YES** ☐ **NO**
Area if Roof has More Than 5% Ponding Water (SF)	
Does the Roof Have Granules/Aggregate/None	
Number of Roof Penetrations (#)	
Total Blisters (SF)	
Delamination (SF)	
Mechanical Damage (SF)	
Bird Pecks (SF)	
Repairs (SF)	
Is the Roof More Than 1% Deteriorated (Yes / No)	☐ **YES** ☐ **NO**
Area if Roof is More Than 1% Deteriorated (SF)	
Coating Type (Acrylic, Urethane, Silicone, etc.)	
Is Roof Recoated? Date if recoated	
Vulnerable Roof Identification	
Average Blister Size on the Roof (SF)	
Any Blisters Over One Foot? (Yes / No)	☐ **YES** ☐ **NO**
Any Open Blisters on the Roof? (Yes / No)	☐ **YES** ☐ **NO**
Does Roof Area have Blisters > 1%? (Yes / No)	☐ **YES** ☐ **NO**

APPENDIX B

NON-PERFORMING ROOFS

Job	Contractor	Job Area	Date Installed	Crit. 1	Crit. 2	Crit. 3	Crit. 4
School 1	A	45,200	7/30/05	N	Y	N	N
School 2	A	85,000	8/26/05	N	Y	N	N
School 3	A	23,000	7/22/05	N	Y	Y	N
School 4	A	32,600	8/1/05	N	Y	N	N
School 5	A	108,000	6/10/05	N	Y	N	N
School 6	A	68,000	7/26/05	N	Y	N	N
School 7	A	57,300	8/3/05	N	Y	N	N
School 8	A	73,000	4/1/05	N	Y	Y	N
School 9	D	6,000	6/3/05	Y	N	Y	N
School 10	D	79,500	2/3/06	N	Y	N	N

Job	Contractor	Job Area	Date Installed	Crit. 1	Crit. 2	Crit. 3	Crit. 4
School 11	A	147,500	8/26/05	N	Y	Y	N
School 12	A	45,200	7/30/05	N	Y	Y	N
School 13	A	12,000	10/21/06	N	Y	Y	N
School 14	A	7,900	4/12/05	N	Y	Y	N
School 15	A	64,700	2/18/05	N	Y	Y	N
School 16	A	23,000	7/22/05	N	N	Y	N
School 17	A	72,600	7/26/05	N	Y	N	N
School 18	A	74,000	8/23/05	N	Y	Y	N
School 19	A	94,100	5/31/06	N	N	Y	N
School 20	A	68,000	7/26/05	N	Y	Y	N
School 21	C	35,200	2/16/06	N	N	Y	N
School 22	C	55,900	3/28/05	N	N	Y	N
School 23	D	55,460	6/3/05	N	Y	Y	N
School 24	D	6,000	12/2/05	N	Y	N	N
School 25	D	1,600	12/28/05	N	N	Y	N