The Thesis Committee for Jorge Mario Blanco Urruchurtu
Certifies that this is the approved version of the following thesis:

Durability of Building Envelope Materials

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor: ______________________________
Atila Novoselac

Co-Supervisor: ______________________________
David W. Fowler

Durability of Building Envelope Materials

by

Jorge Mario Blanco Urruchurtu

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Dedication

To my parents, Bertha y Luis Felipe, to my brother, Sergio Andrés, family, and friends.

Abstract

Durability of Building Envelope Materials

Jorge Mario Blanco Urruchurtu, M.S.E.

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Supervisor: Atila Novoselac

Co-Supervisor: David W. Fowler

This thesis is part of a series of documents that presents some research on different topics that are being conducted at The Durability Lab of The University of Texas consisting of groundbreaking research focused on the durability of building envelope materials used in construction.

Behavior of stucco was analyzed when different construction joint configurations were used, Strict and Compromise cases (accepted by the ASTM standard) and Usual case (often used in construction). These cases were used, in a wall constructed at the exposure site at The University of Texas Pickle Research Campus to compare the joint opening widths due to temperature and weather conditions by installing gage points on both sides of the construction joints.

Water-resistive barrier testing is ongoing as well as nail sealability testing, observations on the performance of products exposed on mockups are being made and the

new implementation of the ASTM D7349, *Standard Test Method for Determining the Capability of Roofing and Waterproofing Materials to Seal around Fasteners*, regarding nail sealability is presented.

Building sealants are crucial when avoiding water to get inside buildings through the perimeters of doors and windows principally. Long-term testing is being done based on ASTM C1589, *Standard Practice for Outdoor Weathering of Construction Seals and Sealants* Procedure C, and important trends are presented after observation and data analysis of the gathered information.

Important takeaways from water-repellent testing are listed considering the behavior and performance of water-repellents based on the effects of UV radiation and weather conditions, as well as the active component and the type of water-repellent.

Construction tapes and flashings are vital in many water-resistive barrier systems, since they seal around all penetrations to provide a complete waterproofing system. Test of construction tapes and flashings has been performed mainly based on ASTM D3654, *Standard Test Methods for Shear Adhesion of Pressure-Sensitive Tapes*, considering different types of tapes and different substrates.

Lastly, the effect of surfactants on the performance of building paper were observed, two different conditions were evaluated: the presence of surfactants on stucco mixes and admixtures, and the presence of surfactants on detergents and soaps used to clean the outer part of buildings.

Some other, but no less important research topics, are ongoing, including properties of plaster mixtures, pedestrian membranes, and elastomeric wall coatings.

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Chapter 1: Introduction

1.1. Background

Envelope materials have played an important role regarding the serviceability of a building. The industry has been moving forward, looking for environmental efficiency and outstanding performance. Many issues and challenges have been faced along the way, with the reliability of materials and the workmanship being the most important ones.

Manufacturers have tried different ways to excel in both. In order to guarantee the proper installation of products, they have started educational programs and certifications for sub-contractors, specifically on the correct application of products. With respect to the reliability of products and materials, manufacturers have improved their innovation and development departments, performing more tests and continuously developing new state of the art standards.

Despite this effort, different problems related to these two vital factors are commonly encountered in practice, setting a critical objective for the coming years. These issues represent a large amount of money for the industry, due to lawsuits and several other expenses. It is necessary to evaluate the performance and durability of envelope materials, doing so will improve quality and optimize operations in both industry and academics.

1.2. Scope of the Research

This research is mainly focused on the performance and durability of materials when exposed to weather conditions in an attempt to simulate actual conditions in practice, which could lead us to a better understanding of the material behavior.

1.3. Significance

In addition to the economic savings, represented by a reduction of maintenance and/or remedial costs, the results of this research may offer valuable feedback for manufacturers, and provide recommendation for changes in standards, which may also improve performance.

1.4. Topics

This document provides updated information on research that has been underway at the Pickle Research Campus of The University of Texas at Austin. The chapters following this introduction detail six specific research topics and the main trends that have been noted over time.

Chapter 2 focuses on the behavior of the stucco used for cladding, regarding the effect of drying shrinkage and temperature on surface cracking of a stucco wall, using different joint configurations exposed to weather conditions.

Chapter 3 contains significant information related to the long-term research on exposed mock-ups of water resistive barriers. Nail sealability testing is also presented, as well as a nail penetration test performed on an integrated WRB.

Chapter 4 consists of testing performed on building sealants exposed to ambient temperature cycles. The evaluation takes place during the interaction between the sealants and two common materials in construction such as concrete and aluminum.

Chapter 5 covers the test done on water repellents and shows a comparison of the performance of different products and the most significant takeaways from the test.

Chapter 6 presents construction tapes and flashing tests based on the ASTM D3654 Standard, which considers different substrates and types of tapes commonly used in construction to evaluate their performance under conditions such as UV exposure, rain, humidity, and temperature.

Chapter 7 includes the study referred to on the effect of surfactants on WRBs, especially on house wraps. For this purpose, RILEM tube testing was done using different types of surfactants combined with distilled water.

Finally, chapter 8 presents the conclusions drawn from the research and recommendations for future practice.

1.5. Objective

In this thesis, the author shows the progress of the research done at The University of Texas at Austin. The data presented, relates the performance of building envelope materials, which may assist in the development of quality control programs. These finding could result in economical savings during and after the construction stage of every research topic of this project.

Chapter 2: Stucco Panel Behavior

2.1. Introduction

One of the most widely used cladding systems is portland cement-based plaster (also known as stucco), composed of portland cement, sand, and water, which in combination with metal lath, construction and control joints, and weep screeds complete the outer part of the building envelope. Despite stucco having been used continuously over time, not much research has been done regarding its performance.

In this chapter, the construction of a stucco panel at the Pickle Research Campus of The University of Texas at Austin is described using different joint configurations, both code and not code compliant, with the intent of promoting cracking when they are exposed to the same weather conditions, including temperature and moisture changes, UV radiation, rain, and wind, among others. Interesting conclusions have been drawn based on recorded data and observations.

Further, prisms samples of the different stucco coats used to build the wall were prepared, and measurements of length variations were taken and compared to the movements of the wall panels observed and recorded using gage points installed on both sides of the joints. A brief description of the construction and the observation processes is presented to show the collected data through charts and tables, which helps to understand the actual behavior of a stucco wall constructed in the field.

The stucco wall panel was built in October 2016, previous students have contributed to define the procedure and the data collection that support the analysis presented in this chapter.

2.2. Stucco Panel

Initially, the main goal of constructing the stucco wall was to evaluate the performance of four different conditions, using cracking of the panels as a reference to assess the functioning of each configuration when exposed to weather conditions. First, a joint configuration compliant with all codes and specifications, where the lath is cut and fixed on one side of the joint and the other side is left free (Strict Configuration). Second, a joint configuration consisting of the cut lath, which is left free on both sides of the joint, as recommended by some experts of the plaster industry (Compromise Configuration). Third, a configuration with a construction joint where the lath is installed continuously; this is commonly used by plaster contractors in practice and supported by another group of experts of the industry (Usual Configuration). Lastly, there was a smaller section where no construction joints were installed, and with lath fastened continuously to the sheathing.

Additionally, some important considerations were followed when designing the dimensions of the wall. To facilitate cracking, an approximate width-to-height aspect ratio of 2.5:1 was established for the biggest panels. However, the smallest section did not follow this aspect ratio since it was intended to serve as a reference for comparison. Three replicate panels with the same joint configuration were built for each case.

Lastly, the complete specifications of the stucco wall comprised a 7 ½-ft by 16-ft wood frame wall constructed using standard 2 x 4 wood framing and oriented strand board (OSB) sheathing. A water resistive barrier (WRB), Tyvek® house wrap, was fastened directly to the OSB, and two layers of No. 15 felt were fastened over the WRB. Three 26-in. strips of lath (one for each specific control joint section) and one 12-in. strip of lath (for the continuous section) were fastened to the wall. Casing beads were placed around the perimeter of the wall, back to back, with a ½-in. gap between control joint sections for sealant. Also, three caliper points were installed on each side of the construction joint in every panel to measure movement over time. The layout of the stucco wall is shown in Figure 2.1.

Currently, the only standardized procedure used to test shrinkage of plaster mixtures is the ASTM C157, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*, which does not consider the presence of the metal lath or the temperature and moisture changes and UV exposure, factors that are essential for a better understanding of the performance and durability of the stucco when used as cladding.

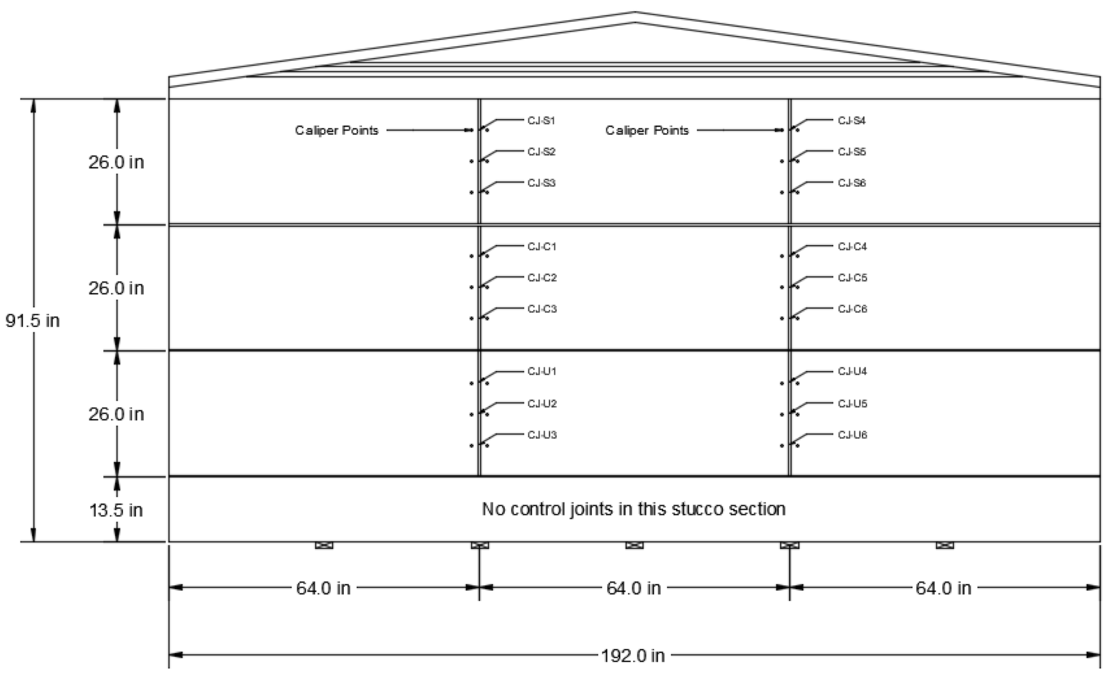

Figure 2.1: Stucco Wall Layout.

2.3. Construction Process

A scratch coat was first applied that consisted of a 1:2:9 ratio of portland cement, masonry cement, and sand respectively. Next, a brown coat consisting of a 1:2:10.5 ratio of portland cement, masonry, and sand was applied 1 ½ hours after application of the scratch coat. After this, in the following day, the wall was moist with a mist spray and cured twice a day for two consecutive days. The finish coat was applied 8 days after the initial application. During the initial 8 days, the temperature ranged from 49 to 92 °F (9 to 33 °C) with an overall mean temperature of 72 °F (22 °C). The relative humidity ranged from 30% to 99% with an overall mean relative humidity of 67%. The ambient dew point was 54 °F ± 5°F (12°C ± 3°C). A photograph of the wall at completion can be seen in Figure 2.2.

Simultaneously, prisms were prepared using both the scratch and the brown coat for the purpose of comparing and recording shrinkage behavior with and without metal lath, and with the mixes being exposed and not being exposed to weather conditions. These prisms were stored inside in a non-air-conditioned or heated space.

Figure 2.2: Stucco Wall at Completion.

2.4. Observations and Discussion about Stucco Panel Behavior

Measurements were taken at 4, 7, 14, and 28 days to check the initial shrinkage of the panel and the prisms. After that point, measurements were taken regularly, generally every two weeks, and special attention was given to cracking of the panels. Subsequently, the surface temperature of the panel and caliper point readings were recorded. The testing data presented in this document in Appendix 1 consist of measurements of the first year of observations for the caliper points installed on the wall and for the shrinkage readings taken on the prisms using a length comparator.

The analysis of all the collected data is presented independently for the stucco panel and for the prisms as well as a comparison plot in Tables 2.1 and 2.2:

Table 2.1: Data Analysis Stucco Panel.

Time (days)	Construction Joint Shrinkage (in.)			Construction Joint Shrinkage (%)		
	Strict	Compromise	Usual	Strict	Compromise	Usual
1	0.0172	0.0228	0.0152	0.0089	0.0119	0.0079
2	0.033	0.0383	0.0308	0.0172	0.02	0.0161
5	0.0382	0.039	0.0323	0.0199	0.0203	0.0168
7	0.0475	0.0495	0.0393	0.0247	0.0258	0.0205
16	0.0708	0.0687	0.0533	0.0369	0.0358	0.0278
21	0.0788	0.0768	0.057	0.0411	0.04	0.0297
28	0.0618	0.0715	0.056	0.0322	0.0372	0.0292
35	0.0562	0.0597	0.0488	0.0293	0.0311	0.0254
49	0.0628	0.0672	0.055	0.0327	0.035	0.0286
93	0.0892	0.098	0.0818	0.0464	0.051	0.0426
125	0.078	0.087	0.0777	0.0406	0.0453	0.0405
153	0.0897	0.0967	0.0803	0.0467	0.0503	0.0418
175	0.0873	0.0935	0.0773	0.0455	0.0487	0.0403
198	0.0715	0.0762	0.0682	0.0372	0.0397	0.0355
215	0.0852	0.0882	0.0757	0.0444	0.0459	0.0394
236	0.0885	0.0962	0.0805	0.0461	0.0501	0.0419
250	0.073	0.078	0.064	0.038	0.0406	0.0333
264	0.0787	0.0813	0.0702	0.041	0.0424	0.0365
278	0.0783	0.0858	0.0765	0.0408	0.0447	0.0398

Table 2.1: Continued

285	0.075	0.079	0.0722	0.0391	0.0411	0.0376
292	0.0778	0.0807	0.0687	0.0405	0.042	0.0358
306	0.0778	0.082	0.0725	0.0405	0.0427	0.0378
322	0.0738	0.074	0.0712	0.0385	0.0385	0.0371
334	0.0703	0.0727	0.0653	0.0366	0.0378	0.034
348	0.0883	0.0943	0.078	0.046	0.0491	0.0406
362	0.0867	0.0945	0.0832	0.0451	0.0492	0.0433

Table 2.2: Data Analysis Stucco Prisms.

Time (days)	**Average Shrinkage (%)**
7	0.0299
14	0.0405
21	0.0452
28	0.0531
35	0.0516
49	0.0541
125	0.0678
153	0.0627
175	0.0653
198	0.0723
215	0.0697
236	0.0661
250	0.0684
264	0.0727
278	0.0747
285	0.0796
292	0.0741
306	0.0811
322	0.0816
334	0.0798
348	0.0781
362	0.0867

It is important to mention that the readings from the prisms were taken starting the seventh day after they were cast as recommended in the ASTM C157 standard. Readings were taken within an hour for both the panel and the prisms to be as consistent as possible with the comparisons.

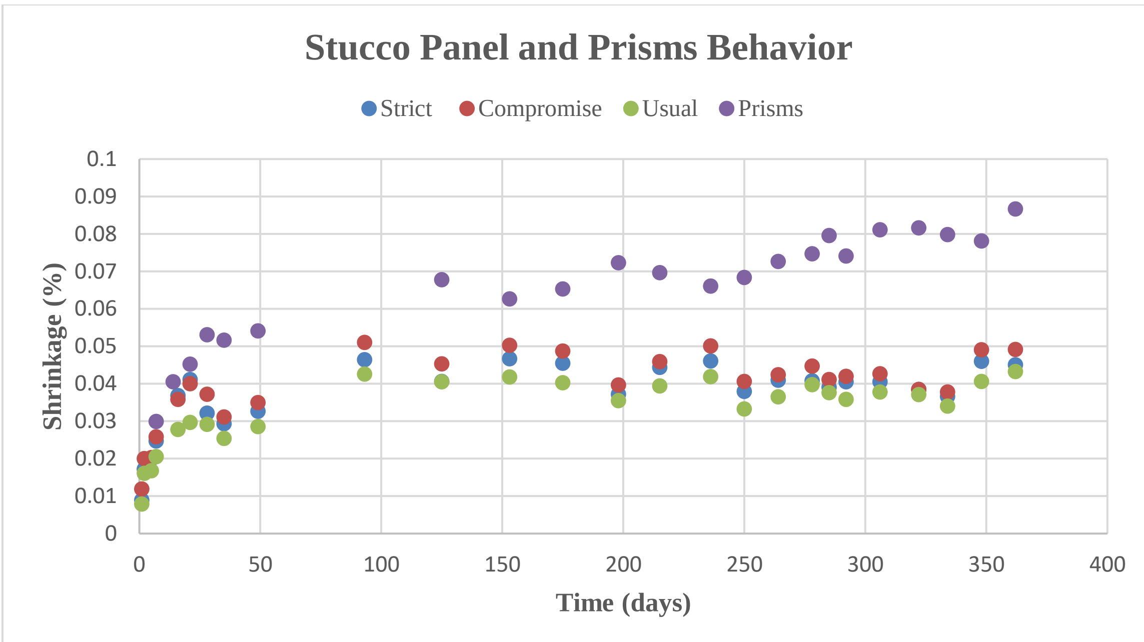

Figure 2.3: Stucco Panel and Prisms Behavior.

Figure 2.3 shows a comparison of the prisms and joint movements. It can be inferred that the metal lath greatly contributes to reducing the effect of shrinkage on the stucco panels. Furthermore, starting from day 93, when the shrinkage percentage stabilized (Figure 2.3), the average difference between the three configurations is around 10%.

Generally, the panels with the usual configuration show that they have experienced less shrinkage, while the panels with the compromise configuration underwent the most shrinkage. Lastly, the shrinkage of the panels with the strict configuration fluctuated between the previous two configurations described above.

The shape of the shrinkage versus time curve shows fluctuations that are most likely due to variation in ambient condition (temperature).

Measurements were taken with high frequency, on an hourly basis, during eight hours on two different days (at day 107 and day114 after casting) to observe the behavior of the panels regarding temperature changes in a single day. The obtained data are presented in Table 2.3:

Table 2.3: Data Analysis Stucco Panel at Day 107 After Casting.

Hour	Hour	Construction Joint Shrinkage (in)			Construction Joint Shrinkage (%)			Surface Temperature (°F)
		Strict	Compromise	Usual	Strict	Compromise	Usual	
1	9:45 a. m.	0.0618	0.0722	0.0645	0.0322	0.0376	0.0336	47
2	10:45 a. m.	0.0623	0.07	0.0625	0.0325	0.0365	0.0326	52
3	11:45 a. m.	0.0623	0.0697	0.0628	0.0325	0.0363	0.0327	51
4	12:45 p. m.	0.0647	0.0705	0.0638	0.0337	0.0367	0.0332	53
5	1:45 p. m.	0.0635	0.0702	0.0628	0.0331	0.0365	0.0327	53.5
6	2:45 p. m.	0.0633	0.0693	0.0623	0.033	0.0361	0.0325	52
7	3:45 p. m.	0.0625	0.0685	0.0613	0.0326	0.0357	0.0319	51
8	4:45 p. m.	0.0618	0.068	0.0602	0.0322	0.0354	0.0313	47

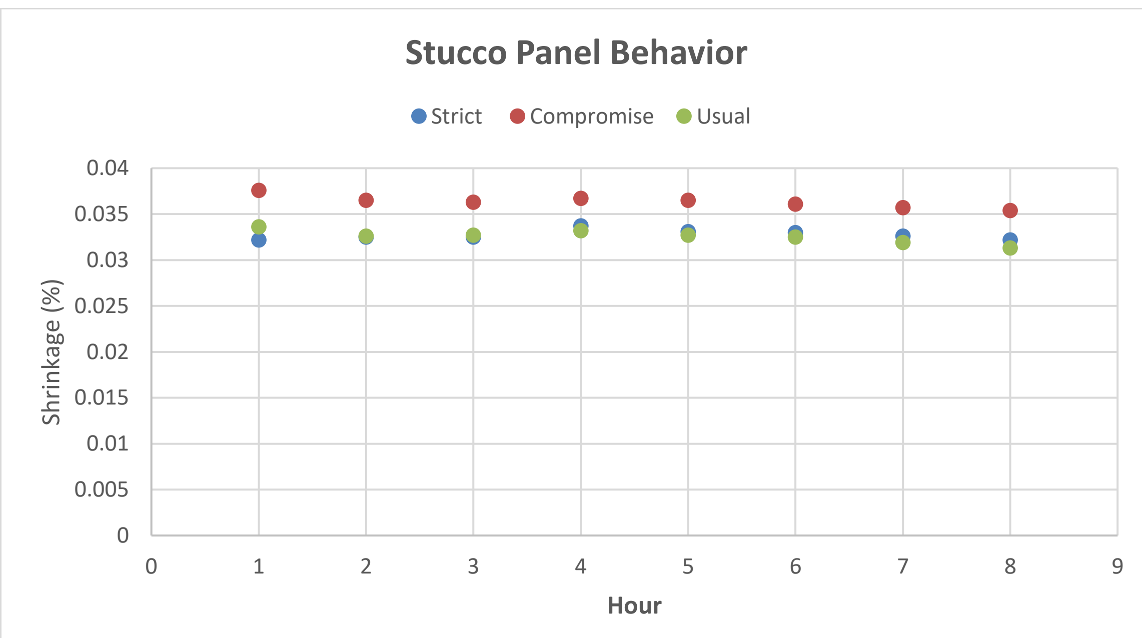

Figure 2.4: Stucco Panel Hourly Behavior at Day 107 After Casting.

In this case, as opposed to the overall behavior of the joint configurations noted before, the difference in movement of strict and usual configurations is shown in Figure 2.4. However, due to a slight change in temperature, little difference in shrinkage is observed for each configuration.

Correspondingly, in Table 2.4, the behavior of both the strict and the usual configurations were again similar as in Table 2.3. Of note is that the maximum surface temperature in Table 2.4 was higher than those in Table 2.3, but the movements were slightly higher than those shown in Table 2.3. Figure 2.5 shows the collected data at day 114 after casting.

Table 2.4: Data Analysis Stucco Panel at Day 114 After Casting.

Hour	**Hour**	**Construction Joint Shrinkage (in)**			**Construction Joint Shrinkage (%)**			**Surface Temperature (°F)**
		Strict	**Compromise**	**Usual**	**Strict**	**Compromise**	**Usual**	
1	9:45 a. m.	0.0612	0.0705	0.0625	0.0319	0.0367	0.0326	63
2	10:45 a. m.	0.0633	0.0705	0.062	0.033	0.0367	0.0323	64
3	11:45 a. m.	0.0643	0.0703	0.0655	0.0335	0.0366	0.0341	76
4	12:45 p. m.	0.0633	0.0708	0.0652	0.033	0.0369	0.0339	77
5	1:45 p. m.	0.0653	0.073	0.0668	0.034	0.038	0.0348	82.5
6	2:45 p. m.	0.0657	0.0748	0.0687	0.0342	0.039	0.0358	87
7	3:45 p. m.	0.0672	0.0757	0.0705	0.035	0.0394	0.0367	93
8	4:45 p. m.	0.0672	0.0753	0.0708	0.035	0.0392	0.0369	89

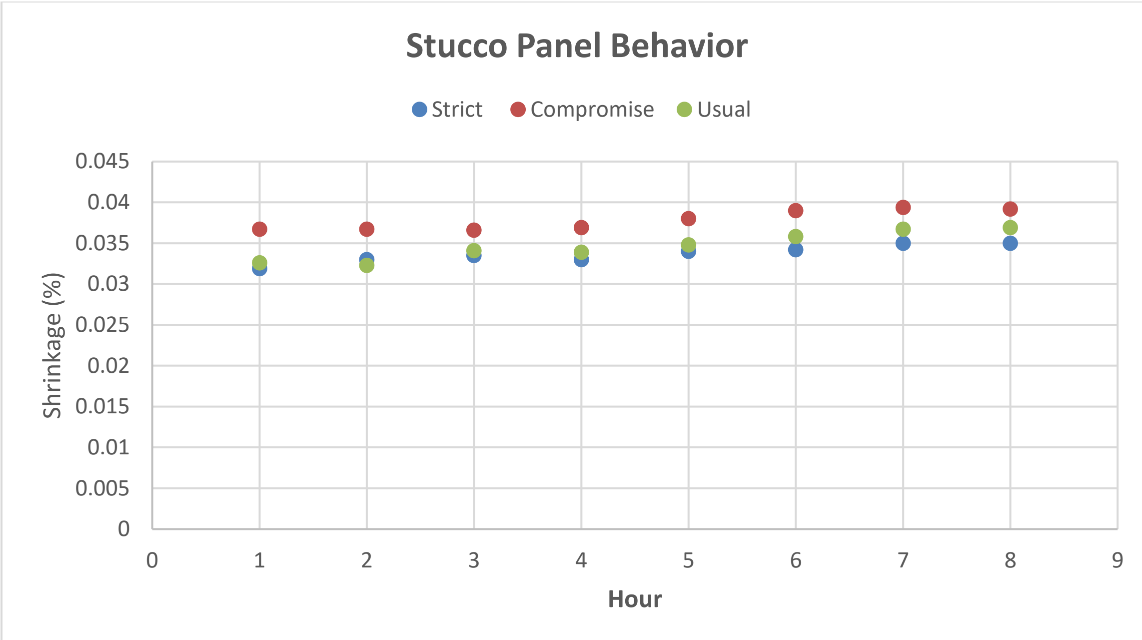

Figure 2.5: Stucco Panel Hourly Behavior at Day 114 After Casting.

Another variable that could affect movement is the moisture content, as discussed in some references. For example, Bowlsby (2010) shows where moisture content is correlated to temperature change. Latta (1962) states:

A differential moisture content through the thickness of a homogeneous material will also have a warping effect, since the side of higher moisture content will expand more than that of the lower. Such a differential moisture content can be produced by vapor migration or by having the opposite sides exposed to different atmospheric conditions. Rain absorbed on the outer face of a material will have a similar effect.

This supports the hypothesis that moisture content may have caused the change in movement when no significant difference in temperature occurred.

In summary, the behavior of the stucco panel is more complex than it was initially thought since the metal lath, the temperature change, the stucco mix, the moisture content, and the type of joint configuration contribute to its final performance, which is not easy to predict.

To consider all these factors, the following testing procedure, which is expected to be implemented in the following months, is proposed:

- Dimensions of the specimens

  Length: 11.25-in. as the drying shrinkage prisms used for ASTM C596

  Thickness: ⅞-in. as specified in ASTM C926 Table 4.

  Width: 4.5-in., to replicate a strip of a stucco wall.

  Number of specimens: 4 units

At the same time, specimens of the same size without metal lath shall be prepared, which includes:

- Temperature of materials: 65°F - 75°F (18°C - 24°C). All proportion of materials to be done by mass. Water and liquids could be done by either mass or volume.
- Mix the mortars in accordance with the ASTM C305 standard. Plaster proportions

  Scratch coat: 1:2:9 ratio of portland cement, masonry cement, and sand.

  Brown Coat: 1:2:10.5 ratio of portland cement, masonry cement, and sand.

  Finish Coat: 1:2:6 ratio of portland cement, masonry cement, and sand.

  Procedure for molding specimens from ASTM C157 9:

Place the mortar in the mold in two approximately equal layers. Compact each layer with the tamper. Work the mortar into the corners, around the gage studs, and along the surfaces of the mold with the tamper until a homogeneous specimen is obtained. After the top layer has been compacted, strike off the mortar flush with the top of the mold, and smooth the surface with a few strokes of a trowel. Immediately after completion of molding, *loosen the device by holding the gage studs in position at each end of the mold in order to prevent any restraint of the gage studs during initial shrinkage of the specimen.*

- Curing. Same procedure as for the stucco panel should be used. Apply the scratch coat, and after it dries apply the brown coat, then cure for two days (moist cured twice a day) and apply the finish coat eight days after the initial application.

  From ASTM C926 X.1.5.2:

  Moist curing is accomplished by applying a fine fog spray of water as frequently as required, generally twice daily in the morning and evening. Care must be exercised to avoid erosion damage to portland cement-based plaster surfaces. Except for severe drying conditions, the wetting of finish coat should be avoided, that is, wet the base coat prior to application of the finish coat.
- One day after applying the finish coat, take the initial comparator reading.
- Take measurements of the specimens at 4, 7, 14, and 28 days when stored at 73 +/- 3 °F [23 +/- 2 °C] and relative humidity of 50 +/- 4 %.
- While the air temperature is 73 +/- 3 °F [23 +/- 2 °C], increase the moisture content of the samples by placing them into a covered plastic container with water, making sure that water is not in contact with the samples. Then, take measurements of the specimens at 4, 7, 14 and 28 days.
- Place the specimens (still inside the plastic container) inside an oven and increase the temperature (the temperature change should be previously determined). Take measurements again at 4, 7, 14 and 28 days. Compare.
- Place the specimens (no plastic container needed this time) inside the oven at the same temperature they were before. Then, take measurements at 4, 7, 14 and 28 days. Compare.

- In each case, in addition to the measurement obtained from the length comparator, moisture content and surface temperature shall be recorded.

It is envisaged that this new test will help to better understand how these variables contribute individually to the global behavior of the stucco used for cladding in practice.

Additionally, special attention has been given to cracking across the panel, since it is known that cracks are the starting point for a potential failure mechanism of the stucco panels, especially when the construction process of the wall does not follow the specifications, and the labor is not skilled.

In this panel, all the cracks have appeared at the bottom of the panel, where no construction joint was installed, confirming the importance of installing them to prevent cracking. Moreover, minor cracks have been noticed at the surroundings of both construction and expansion joints, but it was considered that those cracks are not of great concern since they are hairline cracks. A sketch of the observed cracks is presented in Figure 2.6.

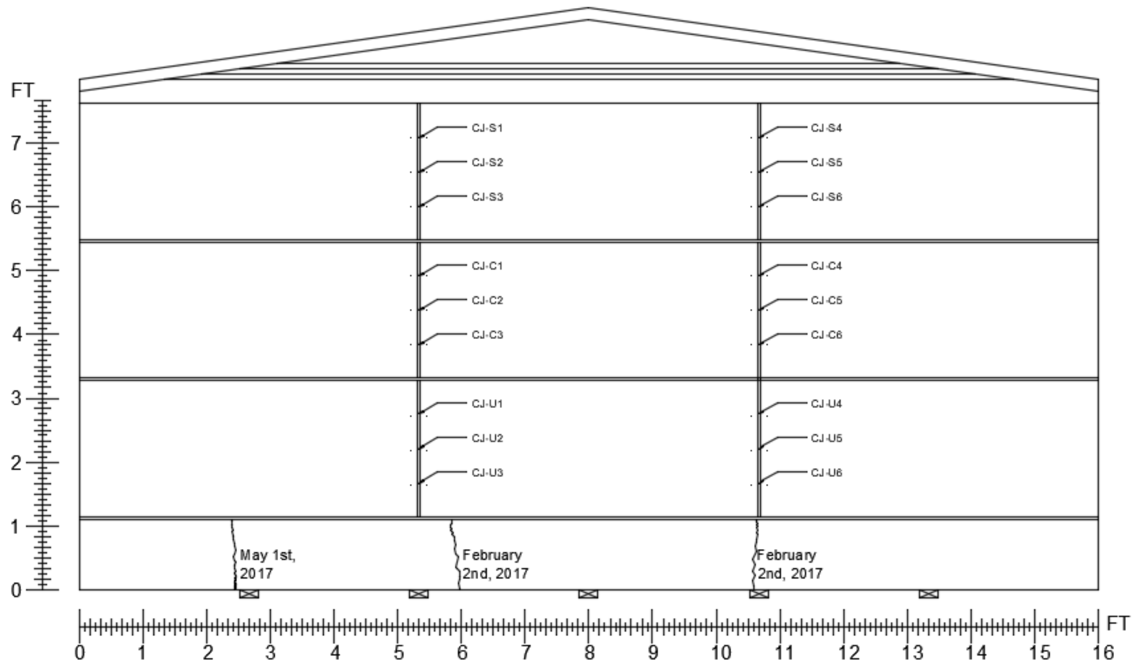

Figure 2.6: Observed Cracks on the Stucco Panel.

There is still more to learn from the durable, and reliable stucco. Measurements should be routinely taken, twice a month, along with the proposed ongoing test, in order to compare and understand the performance of the stucco. It is also intended to identify the deficiencies in actual specifications, codes, and construction processes.

Chapter 3: Water-Resistive Barriers Testing

3.1. Introduction

Water-resistive barriers (also referred as WRBs) prevent water from penetrating a building. This makes them a vital component of the building envelope. Currently, there are different types of water-resistive barriers such as self-adhered sheets, mechanically fastened sheets, fluid applied products, integrated to sheathing barriers, wraps, building papers, and felts. Additionally, water-resistive barriers could be air barriers and vapor barriers. The latter are classified in four types: impermeable, semi-impermeable, semi-permeable, and permeable. This variety of WRBs allows builders to set different configurations and systems depending on the job conditions and requirements.

Since water-resistive barriers are a critical component of the building envelope, special care should be given to the selection process, which includes important factors such as UV radiation exposure, ease of installation, workmanship, and climate, among others. Given the great number of manufacturers and products offered on the market, it is essential to select a product that will not cause concern about its real performance and reliability.

A durability test of these barriers is taking place at The Pickle Research Campus of The University of Texas at Austin, where relevant takeaways have been inferred and discussed in the following section, in addition to the ambient conditions that at the same time affect the performance and integrity of representative products. Since this test was conceived as a long-term test, several students have documented observations over time regarding the WRBs and the nail sealability tests. However, the integrated to sheathing WRB test was recently performed as a complement of the ongoing research.

3.2. Background and Testing Standards

Given the variety of water-resistive barriers available on the market, it is difficult to define a specific test method to assess their performance regardless the type of barrier. Chronologically, felts were the first type of barriers used in construction, followed by papers and wraps (also known as mechanically fastened sheets), and self-adhered sheets. The most recent types of WRBs are the fluid applied products.

Technological and knowledge development, and the permanent effort made to produce environmentally friendly and equally efficient technologies, have resulted in a great number of product offerings. There is a necessity to define common properties that can be compared and evaluated through individual standards, most importantly, water resistance, vapor transmission, air permeance, air leakage, sealability, tensile strength, adhesion, crack bridging, and water penetration.

To simplify the process of evaluating the performance of the water-resistive barriers, several acceptance criteria have been established. Two of them are the AC38 and the AC212, both proposed by the International Code Council Evaluation Service with regard to water-resistive barriers and water-resistive coatings respectively. Some of the proposed test methods for barriers are: (1) weathering tests (Ultraviolet light exposure) and water-resistant tests (based on ASTM D779, *Standard Test Method for Determining the Water Vapor Resistance of Sheet Materials in Contact with Liquid Water by the Dry Indicator Method*), (2) water ponding tests, and (3) drainage tests (based on ASTM E2273, *Standard Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies*).

For paper-based barriers, the AC38 acceptance criteria recommends the following three important tests: dry tensile strength (ASTM D828, *Standard Test Method for Tensile Properties of Paper and Paperboard Using Constant-Rate-of-Elongation Apparatus*), water resistance (ASTM D779 as mentioned before), and water vapor transmission (ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials* - Desiccant Method at 74.3ºF (23ºC)).

Felt-based barriers are required to comply with ASTM D226, *Standard Specification for Asphalt-Saturated Organic Felt Used in Roofing and Waterproofing*.

Polymeric-based barriers should also comply with the dry tensile (ASTM D828), as an alternative, the ASTM D882, *Standard Test Method for Tensile Properties of Thin Plastic Sheeting* is accepted. Additionally, the ASTM D5034, *Standard Test Method for Breaking Strength and Elongation of Textile Fabrics (Grab Test)* should be performed to test the dry breaking force. Furthermore, ASTM D779 and ASTM E96 are tests that are required.

Air barriers should comply with the ASTM E2178, *Standard Test Method for Air Permeance of Building Materials*, which minimum conditions of acceptance shall be an air permeance less than or equal to 0.02 L/(s·m2) @ 75 Pa (0.004 cfm/ft2 @ 0.3 in. w.g. (1.57 psf)) for all three specimens.

In accordance with the AC212 Acceptance Criteria, water-resistive coatings should comply with several ASTM Standards:

- Tensile Bond. ASTM C297, *Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions*.
- Freeze-thaw. A replicate of a treated joint using the water-resistive barrier on five different specimens is exposed to 10 freezing and thawing cycles with temperatures ranging from -20 ºF (-29 ºC) up to 120 ºF (49 ºC).
- Water-resistance. ASTM D2247, *Standard Practice for Testing Water Resistance of Coatings in 100 % Relative Humidity*.

- Water-vapor transmission. ASTM E96, *Standard Test Methods for Water Vapor Transmission of Materials – Water Method.*
- Water-penetration. ASTM E331, *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference*.
- Racking. ASTM E72, *Standard Test Methods of Conducting Strength Tests of Panels for Building Construction*.
- Weathering test. Specimens are exposed to UV lighting, accelerated weathering, and hydrostatic pressures using special chambers.

Currently, there is no long-term test that permits evaluation of the behavior and performance of the water-resistive barriers exposed to real weather conditions. The latter is the principal motivation for conducting this research on water-resistive barriers since very few or no real data are accessible at this time.

3.3. Testing of Water-Resistive Barriers

Representative products were exposed to ambient conditions using full-scale 2-ft × 3-ft mock-ups horizontally oriented on metallic racks facing south, to obtain the most sun exposure, so the potential degradation and effect of UV radiation on the WRBs would be accelerated.

The product application followed the manufacturers' recommendations and technical data. Also, usual details were replicated such as pipe penetrations (tap water pipe, electrical penetrations, either for conduit or for electrical boxes), corrugated brick ties, window flanges, sheathing joints, and outside corners.

A sketch of a typical mockup is shown in Figure 3.1(Feero 2015).

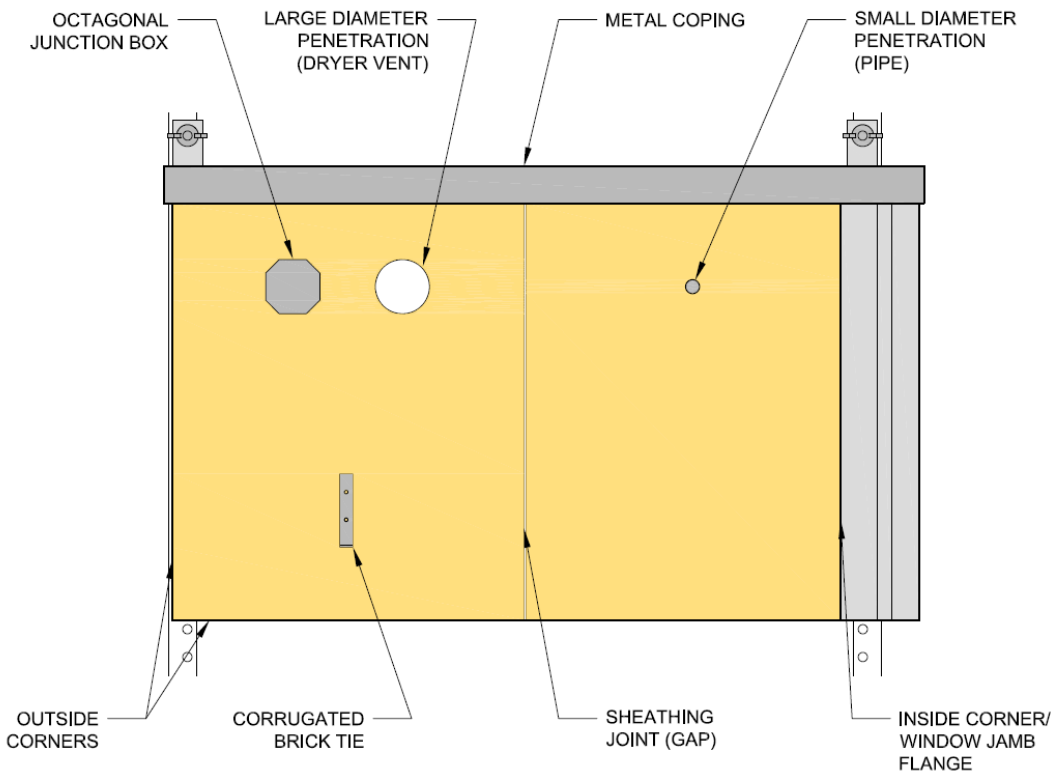

Figure 3.1: Typical Configuration of a Mockup (Ferro 2015).

Each specimen was exposed to ambient conditions until the maximum recommended exposure time was reached based on the product data sheet provided by each manufacturer. Consequently, a fiber cement cladding was installed on the top half of the specimen to monitor the differences in the appearance of each half when UV exposure is continued, and not, principally, when some damage has been induced. Figure 3.2 shows the exposed WRBs at the exposure site at The University of Texas at Austin.

Observations have been made to identify trends and typical failure mechanisms that help the producers to reformulate their products or update their documented literature. Table 3.1 shows the quantity and type of WRBs used for this test.

Table 3.1: Types of WRBs used for testing.

Type of WRB	Quantity	Percentage (%)
Self-Adhered Sheet	3	13.0%
Fluid Applied	17	73.9%
Mechanically Fastened Sheet	2	8.7%
Integrated with the Sheathing	1	4.3%
Total	**23**	**100.0%**

Figure 3.2: WRB Mockups at the Exposure Site.

3.4. Testing of Nail Sealability of Water Resistive Barriers

As stated in Feero's Thesis Document (2015), the nail sealability test most commonly used by manufacturers was ASTM D1970, *Standard Specification for Self-Adhering Polymer Modified Bituminous Sheet Materials Used as Steep Roofing*

Underlayment for Ice Dam Protection, which initially was conceived for self-adhering sheets utilized in roofs. After testing the WRBs in accordance with the latter standard, almost all the products failed because the two nails nailed at the middle of the 1-ft x 1-ft plywood piece were pulled out approximately 0.25-in. before testing.

Simultaneously, the ASTM Committee D08 on Roofing and Waterproofing approved the ASTM D7349, *Standard Test Method for Determining the Capability of Roofing and Waterproofing Materials to Seal around Fasteners,* in which several protocols were established to account for different parameters. It is interesting that these standards were developed for roofing materials testing.

A new round of nail sealability test was performed on numerous products according to the ASTM D7349 Protocol 4, except for not using the intervening material, and using at least three specimens of each product. The most substantial change between these two standards resides in the fact that the nails were not pulled out as stated in ASTM D1970 before erecting a water column over the test assembly. Figure 3.3 shows the test assembly described by the ASTM D7349.

The ASTM D7349 is not intended for fluid applied products. However, they were tested because some manufacturers claim that their products have the capability to seal around fastener penetrations.

Figure 3.4 shows one round of testing in accordance with ASTM D7349.

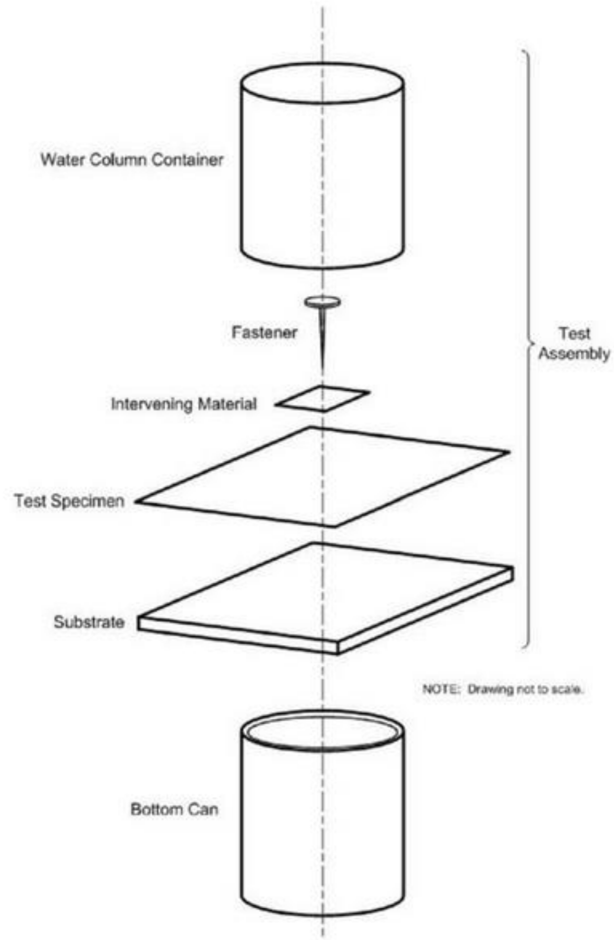

Figure 3.3: Test Assembly in Accordance with ASTM D7349.

Figure 3.4: Test Assembly of Nail Sealability Testing.

3.5. Testing of Integrated to Sheathing WRB

The interest to evaluate the performance of this type of WRB motivated a real case study, and a test was run at the Pickle Research Campus at The University of Texas at Austin. A WRB integrated to the sheathing was tested using a RILEM tube under different conditions with regard to how the sheathing was attached to the wood framing. The test mimicked a critical condition, relating the combined effect of water ponding caused by the wrong installation of sealants around a window opening, and the presence of fasteners, studs, and flashings.

Several cases were considered for the testing: no nail, nail flush, head deep (head of the nail slightly pushed into the sheathing), overdriven (head of the nail causing some damage to the outer surface of the sheathing), and head above. These cases were tested with and without tapes and wood studs. Examples of the test assemblies described above are shown in Figures 3.5 and 3.6.

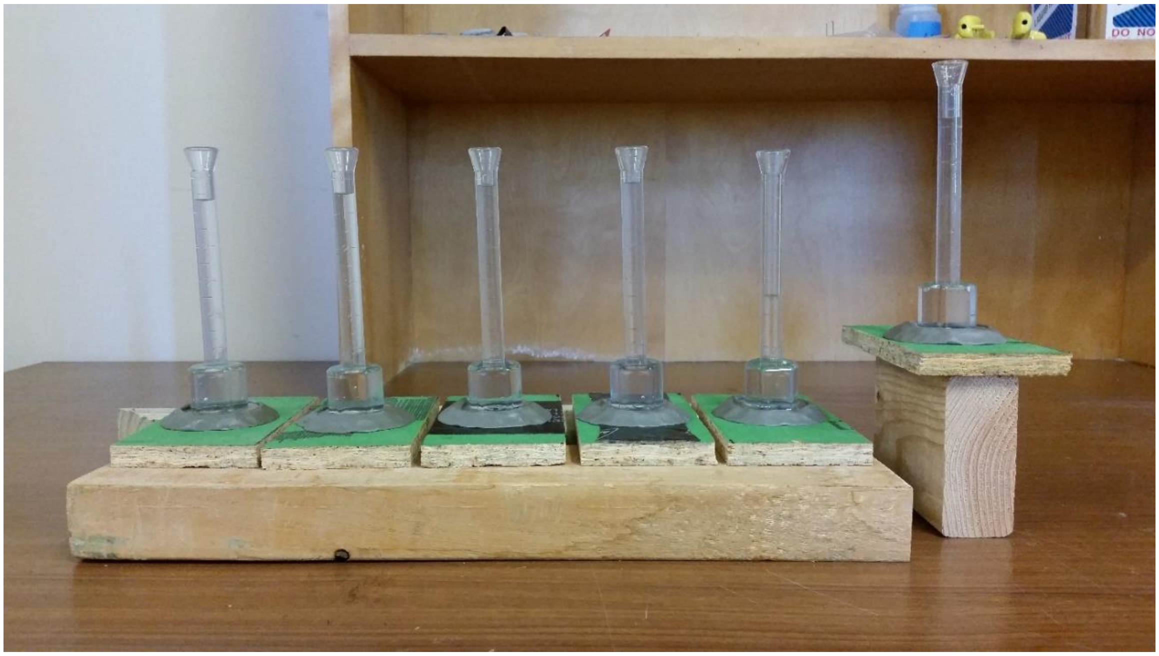

Figure 3.5: Integrated to Sheathing WRB Testing.

Figure 3.6: Other Testing Configurations for Integrated to Sheathing WRB.

3.6. Observations and Discussion about the WRB Testing

Several main failure mechanisms were identified during the ongoing test. Different parameters such as the type of WRB, flashing products and details, and the manufacturer's recommendations for each case were considered. Also, the frequency of occurrence, similarities among products, and failure mechanisms are listed.

The first observed mechanism was the discoloration, primarily related to sun exposure and dirt pick up, with an occurrence of 74% among the tested products. UV radiation could induce damage to the surface of the membrane, which is evidenced by the change of color. Sometimes this mechanism has no consequences on the performance of the barrier, but it could serve as a starting point for other mechanisms, since in most of the cases, the WRB gets somehow "weaker". Furthermore, discoloration can also be a result of the combination of water and dirt accumulated at some points of the membrane, and depending on the material and ambient conditions, several chemical reactions could develop, resulting in a change of color. Figure 3.7 shows a specimen showing discoloration.

Figure 3.7: Specimen DRP1009-24 7 Months After Exposure Showing Discoloration.

Cracking is considered a great concern when evaluating the performance of WRBs since they represent a path for water going from the outer to the inner part of the building, increasing the probability of failure of the waterproofing system and, of course, the building envelope. Cracking mechanism is the second most common mechanism with a 65% of occurrence. There are diverse causes for cracking membranes: reflection of the wood grain (wood sheathing) because of solar damage, changes in temperature, and a combination of both. This type of mechanism is often noted in fluid-applied membranes, as well as in the integrated WRB sheathing, and in some mechanically fastened sheets. Figures 3.8 and 3.9 show different cracking patterns observed on two specimens.

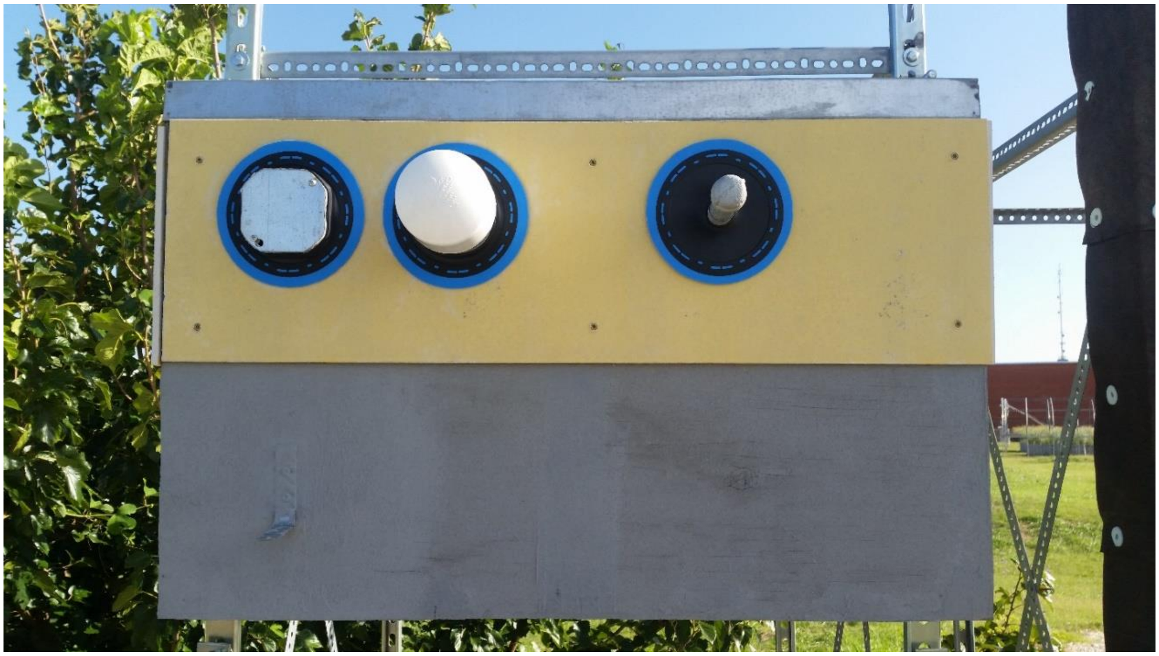

Figure 3.8: Specimen DRP1009-19 9 Months After Exposure. Horizontal Cracks Noticed at the Uncovered Part.

Figure 3.9: Specimen DRP1009-16 Crazing Observed After 3 Years of Exposure.

Cratering (pinholes) is a unique phenomenon of fluid applied products; 59% of the exposed products show pinholes and/or craters on their surfaces. In a few cases, these craters go through the product reaching the sheathing. Pinholes are considered a result of weather exposure. Examples of this phenomenon are presented in Figures 3.10 and 3.11.

Figure 3.10: Pinholes Noted on Specimen DRP1009-24 Before the End of UV Permitted Exposure Time.

Figure 3.11: Specimen DRP1009-01 3 Years and 11 Months After Exposure.

Fishmouthing is commonly detected in self-adhered sheets and flashing accessories of mechanically fastened sheets. This mechanism is characteristic of asphalt-based products, but can also be found on acrylics and butyl based products, and is related to temperature changes over time, specifically when high temperatures are involved. A case where fishmouthing was observed is presented in Figure 3.12.

Figure 3.12: Fishmouthing Along the Flashing at The Window Flange Noticed in Specimen DRP1009-02.

Washing the membrane is a mechanism directly related to rain and water rundown that happens exclusively to fluid applied products. In this test, 18% of the fluid applied products have washed away, causing a reduction of the dry film thickness of the membrane, which derives from a decrease of the effectiveness of the system. Water-sensitive products exhibit this type of degradation in some cases much before the end of the exposure time recommended by the manufacturer. Figure 3.13 shows the described mechanism.

Figure 3.13: Specimen DRP1009-03 2.5 Years After Cladding Installed. The Exposed Part Has Washed Off.

Dirt accumulation is the third most common mechanism with an incidence of 52% overall. Accumulation of dirt on the surface of the WRB should be addressed carefully given that some microorganisms could be born when organic materials are used in the product preparation, producing an increase in the degradation rate. On the other hand, dirtiness could be just a result of the mixing of water and dust across the mock-up, principally at non-flat locations. Figures 3.14 and 3.15 show the accumulation of dirt across the specimen.

Figure 3.14: Dirt Pick Up of Specimen DRP1009-11 After Siding Removal 3 Years and 3 Months From Exposure.

Figure 3.15: Dirtiness Evidenced in Specimen DRP1009-14 When Siding Removal After 3 Years of Exposure.

Blistering, also known as air bubbling, is related to the limited capability of the barrier to let air or vapor get out from the inner part of the building. This is likely to happen to fluid applied products, but this has also been observed in self-adhered sheets and in the integrated to sheathing WRB. At those spots, the membrane is not properly attached to the sheathing, which increases the chances for the membrane to fail, making it more vulnerable to weather conditions. This can be observed in Figure 3.16.

Figure 3.16: Specimen DRP1009-07 with a Great Number of Air Bubbles after 3 Years 9 Months of Exposure.

Waviness is a mechanism that appears only in self-adhered and mechanically fastened sheets; waviness is represented in 17% of exposed specimens on the racks. This mechanism differs from fishmouthing because it does not happen only along the edges of the sheet, instead it could be spotted across the entire membrane as an effect of ambient conditions, which include temperature, rain, wind, and sunlight. Figures 3.17, 3.18, and 3.19 show the described waves across the specimens.

Figure 3.17: Specimen DRP1009-12 Waviness at Covered Part.

Figure 3.18: Specimen DRP1009-06 Vertical “Waves” Noted at the Uncovered Part 3 Years 3 Months After Exposure.

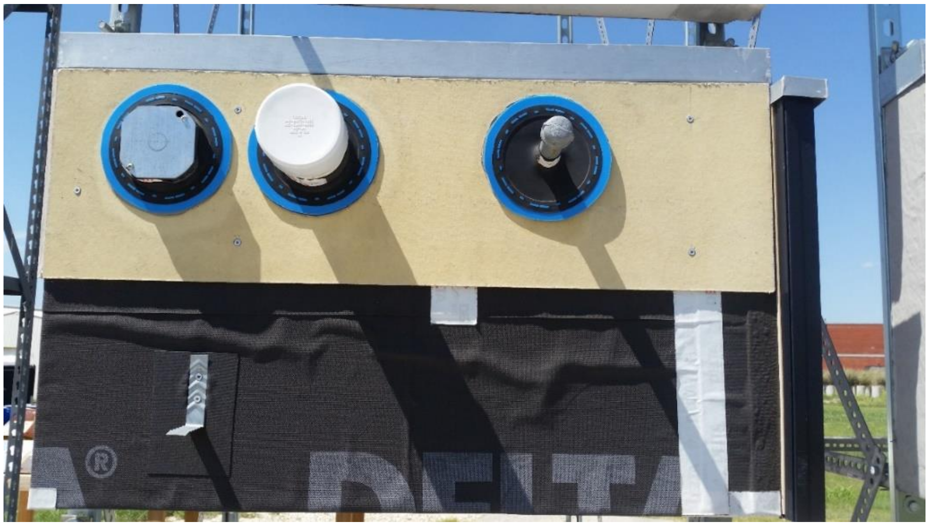

Figure 3.19: Specimen DRP1009-15 3 Years 4 Months After Exposed. Waves Noted at the Uncovered Part Due to Air Bubbles.

Peeling and/or tearing is a follow-up or second-order mechanism. This means that it comes after another mechanism such as cracking or blistering, making it easy for the cracked membrane to peel, as in the case of a fluid applied product, or tear if mechanically fastened or self-adhered sheets are used. Once a WRB product starts migrating from the sheathing, it has no functionality at all, and since the sheathing is totally exposed, water can directly damage either the framing or the interior finish of a building. Figures 3.20 and 3.21 show how the WRB is tearing and peeling, respectively.

Figure 3.20: Tearing of Specimen DRP1009-09.

Figure 3.21: Peeling of Bottom Edge Specimen DRP1009-04.

In general, weather conditions play an important role when the performance of WRBs is evaluated, even after the cladding has been installed. It was noticed that the initial mechanisms that started before the installation of the Hardie Board continued progressing but, as expected, at a slower rate. Additionally, it was observed that in some cases, the cladding could not be removed from the mock-up after a certain amount of time. This type of mechanism is denominated as ambient sensitive because weather conditions, principally temperature and rain, can cause serious issues to the integrity and performance of the WRB.

Table 3.2 shows the summary of mechanisms noted in each tested product and its corresponding accessories. Figure 3.22 shows a bar graph relating the type of failure mechanism with their observed frequency.

Table 3.2: Failure Mechanisms of WRBs.

Product Name	Discoloration	Cracking	Cratering/Pin Holes	Fishmouthing	Washing Off/Wearing Away	Dirtiness	Air Bubbles/Blistering	Waviness	Peeling/ Tearing	Ambient Sensitive (Temp, Weather)
DRP1009-01			1		1	1	1			
DRP1009-02	1							1	1	
DRP1009-03	1	1			1	1				
DRP1009-04	1	1	1			1			1	
DRP1009-05	1	1	1	1		1	1		1	
DRP1009-06		1		1		1		1	1	
DRP1009-07		1	1			1	1			1
DRP1009-08	1	1	1			1				1
DRP1009-09	1	1	1			1	1		1	
DRP1009-10	1	1		1			1			
DRP1009-11			1			1	1			
DRP1009-12	1	1						1		1
DRP1009-13	1	1			1				1	
DRP1009-14	1		1			1				
DRP1009-15				1			1	1	1	1
DRP1009-16	1	1	1			1	1			1
DRP1009-17	1	1	1			1			1	
DRP1009-19	1	1								
DRP1009-20	1									
DRP1009-21										
DRP1009-22	1			1						1
DRP1009-23	1	1								
DRP1009-24	1	1								
Total	17	15	10	4	3	12	8	4	8	5
Total (%)	73.9%	65.2%	43.5%	17.4%	13.0%	52.2%	34.8%	17.4%	34.8%	23.8%

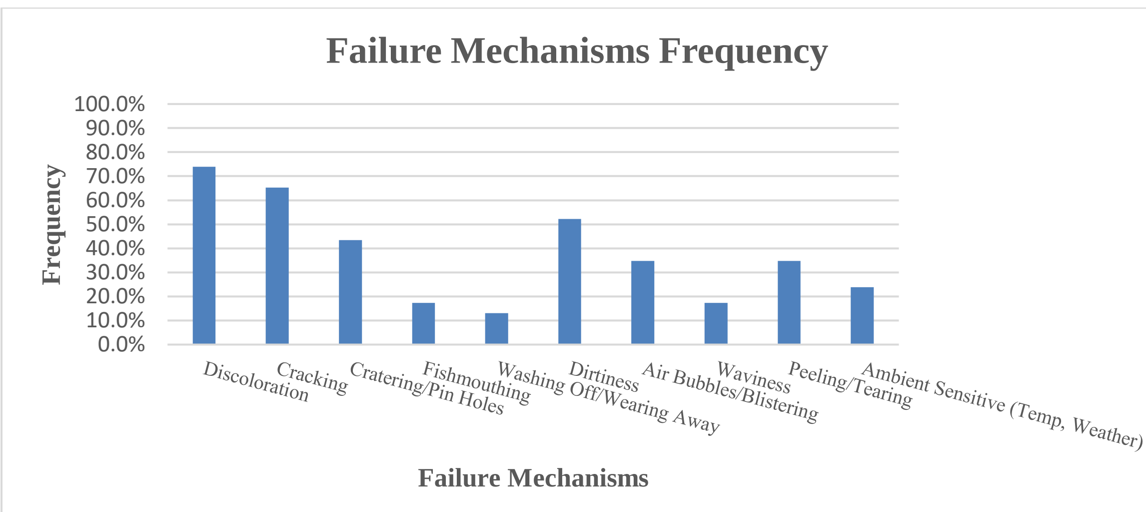

Figure 3.22: Frequency of Failure Mechanisms.

3.7. Observations and Discussion over Nail Sealability Testing

The second round of nail sealability testing showed a better overall efficacy of all the tested products since many of them sealed efficiently around the nail penetrations with the flushed nail. The percentage of passed specimens increased by a little more than 3 times, while the fail percentage decreased by approximately 4 times. A comparison between the results of both rounds of testing is presented in Table 3.3**.**

Table 3.3: Comparison of Results from Nail Sealability Test: ASTM D1970 and ASTM D7349.

ASTM Standard	Products Tested	Results			
		Pass		Fail	
D1970 - Until 2014	16	4	25.00%	12	75.00%
D7349 - From 2015	12	10	83.33%	2	16.67%

These results confirm that the critical scenario resulting from the two pulled out nails from the plywood piece was extremely severe for the barriers to overcome. Additionally, as opposed to roof materials, the WRBs are installed vertically, thus decreasing the probability of having such a critical scenario defined by the ASTM D970.

Although this test is not intended for water-resistive barriers, it is possibly a good way to evaluate the performance of sealing penetrations. There could be value in developing a test standard that assists in the assessment of all the existing types of WRBs.

Data obtained from this test is presented in Appendix 2.

3.8. Observations and Discussion over Integrated to Sheathing WRB Testing

After testing the performance of the integrated to sheathing WRB, several failure modes were identified, such as water going down alongside the shank of the nail; water going through the layers of the OSB and falling from the edges of the sheathing; and water going through the layers of the OSB without falling from the edges of the sheathing. Figures 3.23, 3.24, and 3.25 show each failure mode.

Figure 3.23: Water Falling From the Shank of the Nail.

Figure 3.24: Water Falling From the Edges of the Sheathing.

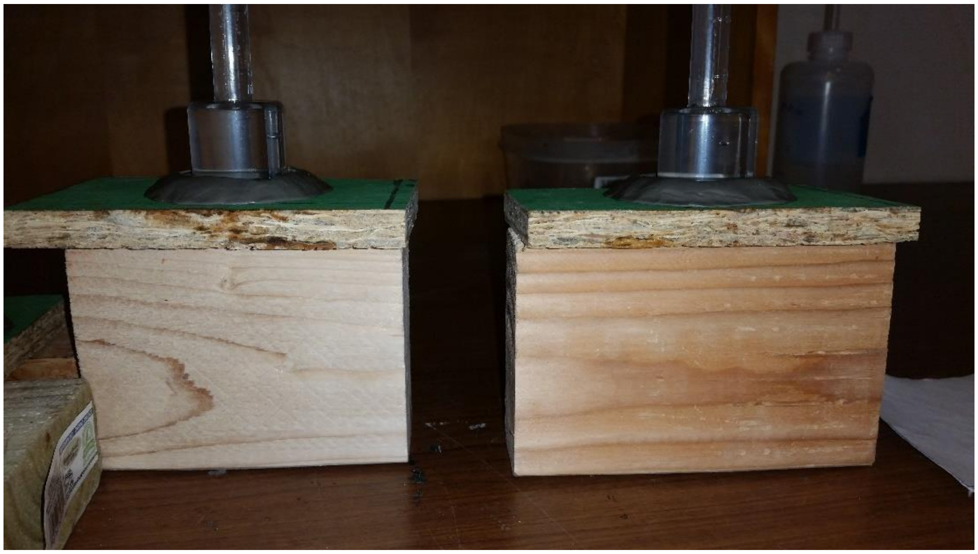

Figure 3.25: Water Going Through the Sheathing.

Various scenarios contributed to the drop in water level in the RILEM tube and are described below:

- Head flush and head above cases could have similar behavior to the head flush case. Sometimes the nail is not properly nailed because the sheathing surface is wavy. Therefore, the space left between the head of the nail and the surface of the sheathing allows water to go inside and/or through the sheathing. This was noticed a few times in the head flush case shown Figure 3.24.
- If the nail causes some damage when it is being nailed at the backside of the sheathing (not the painted side), parts of the OSB board may break apart or detach. This could create a weak area where water can easily go through the sheathing or fall along the shank of the nail as drops.
- When tapes were installed before nailing the nail, they sealed around the nail penetration in most of the cases. The stretch tape performed better than the flashing tape.

- The overdriven case is not always the worst performer. Outcomes could be related to the level of compactness of the sheathing at the nail's specific location and its surroundings.
- The wood stud could facilitate the flow of water to the edges of the sheathing (as in this test) or to the parts surrounding the nail. Also, the amount of water absorbed might depend on the level of compactness of the sheathing.
- As expected, no nail and head flush showed the best performance overall. It is important to mention that head above over stretch tape also performed well due to the sealing effect of the tape.

Collected data from this test are shown in Appendix 3.

The most important takeaway of this test consists of the need to seal every penetration caused by nails to the integrated to sheathing WRB since there is a high chance of water causing some deterioration and/or rotting to the board if the construction process of the building envelope does not comply with the specifications.

Chapter 4: Building Sealants

4.1. Introduction

Building sealants are widely used at construction joints, which can be between the same material or two different materials at both sides of the joint. They are usually located at the exterior part of the building, so they are exposed to weather conditions, UV radiation, and movement of the building.

Sealants should be able to resist and adapt to those changing conditions while providing waterproofing and maintaining their integrity for a long-term service life. Manufacturers have used different materials to accomplish that task such as urethanes, silicones, and hybrids.

Urethanes are organic products, this makes them sensitive to UV radiation and weathering. On the other hand, silicones are known to be inorganic products, so they are not sensitive to UV radiation. Lastly, hybrid sealants try to combine the best properties of urethanes and silicones to produce a well-rounded product.

The test presented herein shows the performance of two different sets of products regarding the type of sealant and some other considerations such as priming and validation criteria. The last two cycles for each set of tests added to the previous information collected by other students served as the analysis data for this chapter.

4.2. Background and Testing Standards

Over time, several standards have been used by manufacturers to observe the performance of building sealants such as ASTM C719, *Standard test method for Adhesion and Cohesion of Elastomeric Joint Sealants Under Cyclic Movement (Hockman Cycle)*, ASTM C793, *Standard Test Method for Effects of Laboratory Accelerated Weathering on Elastomeric Joint Sealants*, and ASTM C1442, *Standard Practice for Conducting Tests on*

Sealants Using Artificial Weathering Apparatus. Others provide guides and specifications regarding the use of joint sealants such as ASTM C920, *Standard Specification for Elastomeric Joint Sealants*, and ASTM C1193, *Standard Guide for Use of Joint Sealants*.

After reviewing these ASTM standards, it is noted that none of them consider a process and/or conditions of weathering and movement, which could serve as a reference to measure the durability of each product. Instead, the initial intent of these standards consists of checking their initial performance in a short period of time, and under ideal conditions that do not depict what it is commonly seen in practice.

The ASTM C1589, *Standard Practice for Outdoor Weathering of Construction Seals and Sealants*, was approved to perform a cyclic test considering three different scenarios: outdoor weathering exposure of the specimens accounting for periodic manual technique (Procedure C); outdoor weathering exposure of the specimen by using a special apparatus (Procedure B), which uses the coefficient of thermal expansion of PVC to induce movement to all the tested specimens; and another testing protocol (Procedure A) which does not contemplate cyclic movement of the specimens.

Using the ASTM C1589 to assess the durability and performance of building sealants, requires a defined, fixed location for the specimens since they can differ significantly, depending on different factors such as solar radiation, moisture, pollutants, temperature, humidity, and others. Furthermore, it may take several years to determine an average result in time for the tested products.

Additionally, the Sealant, Waterproofing, and Restoration Institute (SWRI) developed an acceptance criterion that requires a sealant to pass both the ASTM C716 and ASTM C920 standards.

4.3. Testing of Building Sealants

Procedure C of the ASTM C1589 standard was started in two different sets of products. Four replicated specimens were prepared from each product, three to be exposed and one to be filed to observe their different behavior. To maximize the effect of solar radiation on the specimens, the rack is going to be installed facing the equator (south) with an angle of 45°.

Specimens consist of a piece of concrete (top) and a piece of aluminum (bottom) joined by ½-in. of sealant (neutral position) applied with and/or without primer. Compression is achieved by reducing the space between the two substrates to 3/8-in., in spring and summer seasons, while expansion sets the spacing up to 5/8-in., in fall and winter seasons.

Six hybrids, 35 silicones, and 18 urethanes were tested in two different sets. The first set of products (32 sealants) was exposed on the rack in May 2014, starting in compression. The second set of products (27 sealants) was exposed on the rack in September 2015, starting in expansion.

When a change of spacing is due, approximately every six months, two different procedures were determined to avoid inducing additional stresses to the sealant as follows:

EXPANSION

1. Remove the specimen from the fixture with a wrench and screwdriver.

2. Remove the ⅜-in. spacers.

3. Using calipers, measure the distance between the aluminum and concrete substrate on the left and right side of the specimen.

4. Close the vises and slide the jaws into the space where the spacers were removed.

5. While holding the specimen, slowly extend the vises until the specimen is held in place by the jaws.

6. Extend the jaws at the rate of 1 cycle (rotation) per minute taking photos at every half cycle. After 2-3 cycles (depending on the compression set) the gap between the substrates should be slightly larger than ⅝-in.

7. Insert a ⅝-in. spacer into the back of the center of the specimen.

8. With the jaws still extended, hold the specimen in place, inch the specimen up so that ⅛-in. of the aluminum and concrete substrates overhang above the jaws.

9. Insert two ⅝-in. spacers on both sides so that they come into contact with the ⅛-in. overhang.

10. Close the vises and carefully remove the specimen.

11. Move the side spacers until they are in their place between the two substrates.

12. Remove the spacer from the back center of the specimen.

13. Place the specimen in the fixture and tighten with a wrench and screwdriver. Using slight hand pressure, tighten until neither the specimen nor the spacers are able to move.

14. Zip-Tie the specimens to the rack.

COMPRESSION

1. Remove the specimen from the fixture with a wrench and screwdriver.

2. Extend the jaws on the vise until they are approximately ⅝-in.

3. Slowly work the specimen onto the jaws while sliding the spacers out of the front.

4. Close the vise slowly until the specimen can be removed.

5. Using calipers, measure the distance between the aluminum and concrete substrate on the left and right side of the specimen.

6. Place the specimen back into the fixture with ⅜-in. spacers in their eventual location between the substrates.

7. Position a C-Clamp over the outside of the fixture with the top and bottom pads of the clamp bearing against the top and bottom plates of the fixture.

8. Compress the C-Clamp slowly until the spacers are lightly in place between the substrates. Be careful not to clamp too hard or the concrete substrate may crack.

9. Tighten the screws on either side of the fixture until the ⅜-in. spacers are firmly in place.

10. Zip-Tie the specimens to the rack.

After each cycle, observations and status of each specimen were made. Additionally, periodic observations (approximately once a month) were made for specimens on expansion cycle.

4.4. Observations and Discussion about Building Sealants

To define the status of every specimen when periodic inspections were done, several statuses were identified (pass, distress, failing, and fail) to keep track of the deterioration of each sample while the test was ongoing.

A specimen was considered to pass (Figure 4.1) when no visible change in the appearance of the sealant was noticed, such as microcracking, debonding from one of the substrates, and pinholes. However, some dirt pick-up is accepted as a normal consequence of weathering.

Figure 4.1: Pass Specimen.

Similarly, a specimen was considered distressed (Figure 4.2) when some deterioration was noted and when it was not possible to see through the specimen. The failing case (Figure 4.3) was considered as a severe distress case, which means that debonding of the sealant from one or both substrates could be observed, or it was possible to see through the sealant. It is important to mention that while failing specimens in practice may be considered as failed specimens, because they no longer fulfill their main function of preventing water from entering the building, they can still be tested for research purposes. Nonetheless, in order to show the data results, failing specimens were counted as failed.

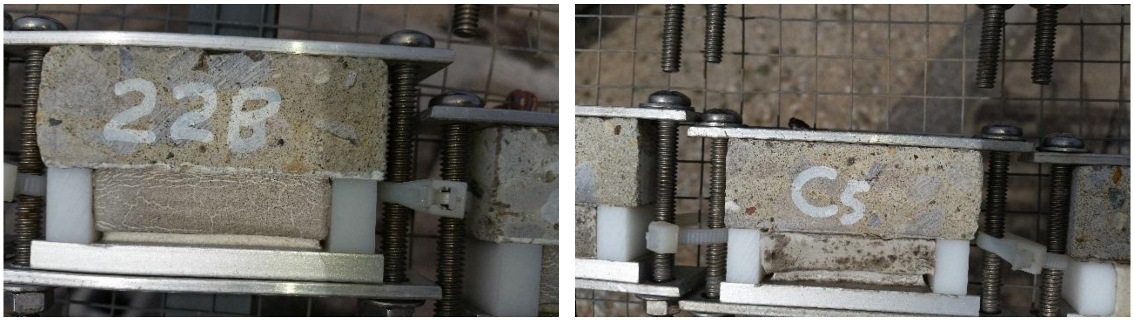

Figure 4.2: Distress Specimen.

Figure 4.3: Failing Specimen.

Lastly, a fail specimen (Figure 4.4) was the one with a severe failing condition, meaning that a great portion of the interaction length of the sealant with either concrete or aluminum substrate was no longer in good condition.

Figure 4.4: Fail Specimen.

Since two different set of specimens were exposed at different times, each one was addressed independently regarding the type of building sealant, primed or unprimed condition, the behavior of the filed specimen, and the validation from SWRI.

The first set of specimens, May 2014, was recently subjected to expansion for the fourth time, and the observed performance is shown in Table 4.1.

Table 4.1: Summary of First Set of Specimens Tested.

Specimen Description		Number of Specimens	Number of Failures	Failure Percentage (%)
Silicone	Primed	60	37	61.67%
	Unprimed	45	29	64.44%
	Filed Specimens	15	5	33.33%
	Total	120	71	59.17%
Urethane	Primed	30	16	53.33%
	Unprimed	24	20	83.33%
	Filed Specimens	8	4	50.00%
	Total	62	40	64.52%
Hybrid	Primed	6	6	100.00%
	Unprimed	3	0	0.00%
	Filed Specimens	2	2	100.00%
	Total	11	8	72.73%
SWRI Validated Products		139	72	51.80%
Non-Validated Products		54	47	87.04%
All Specimens		193	119	61.66%

It can be inferred that silicone sealants are the best performers of the three types overall. Also, their efficacy is not significantly different whether the product is applied with or without a primer. Since silicones are inorganic sealants, and hence not UV radiation sensitive, it could be expected that the failure percentage of exposed specimens might be similar to the specimens left indoors (filed specimens), which perform even better when silicones alone are considered. This phenomenon could be the result of different manufacturing processes and/or techniques, leading somehow to a certain degree of solar radiation sensitivity.

Primed urethanes, when compared to primed silicones and primed hybrids, perform better. This means that urethanes must be applied using primers to have the best performance during their service life. On the other hand, unprimed urethanes have a high failure percentage, around 80%. Half of the filed urethanes specimens have failed so far, yielding the lower failure percentage of this set of specimens. At the same time, stored urethanes deteriorate and fail faster than silicones.

In this set, 11 hybrid sealants are being tested, and the results obtained to date indicate that hybrids have an outstanding performance when no primer is used. Additionally, all the primed hybrid specimens, exposed and filed, failed. This is a clear and valuable conclusion, which could encourage manufacturers to conduct further research and development of hybrid compounds. Figure 4.5 summarizes the results of this part of the test.

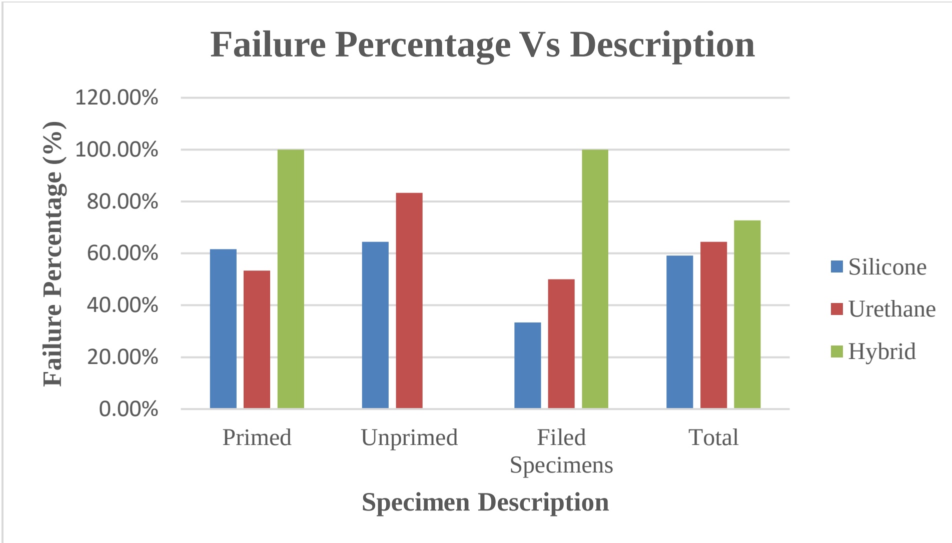

Figure 4.5: Failure Percentage of First Set of Testing.

Regarding the validation of the products, the SWRI validated products perform relatively better than non-validated products. However, half of the validated products have failed up to this time of the testing as shown in Figure 4.6.

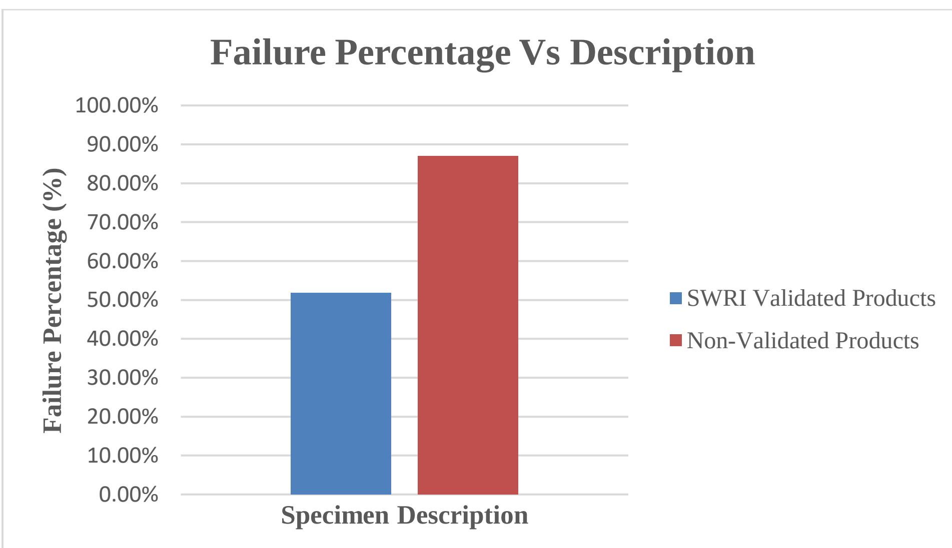

Figure 4.6: Failure Percentage of Validated and Non-Validated Products – First Set of Testing.

The second set of specimens, September 2015, has just been set to its third expansion cycle. Table 4.2 shows a summary of the test results. This second round of testing focused mainly on primed specimens, following the manufacturers' instructions for the given products.

Table 4.2: Summary of Second Set of Specimens Tested.

Specimen Description		Number of Specimens	Number of Failures	Failure Percentage (%)
Silicone	**Primed**	45	12	26.67%
	Unprimed	0	0	0.00%
	Filed Specimens	15	2	13.33%
	Total	60	14	23.33%
Urethane	**Primed**	30	11	36.67%
	Unprimed	0	0	0.00%
	Filed Specimens	10	1	10.00%
	Total	40	12	30.00%
Hybrid	**Primed**	12	9	75.00%
	Unprimed	0	0	0.00%
	Filed Specimens	4	3	75.00%
	Total	16	12	75.00%
SWRI Validated Products		68	19	27.94%
Non-Validated Products		48	19	39.58%
All Specimens		116	38	32.76%

Silicone products are performing better than the rest, but in this case, urethanes' failure percentage is significantly lower (30%) than on the first round of testing (64.52%). This could be because the sealants have been exposed for less time, so the degradation due to weathering and solar radiation has had less affected on their performance. It is also possible that the manufacturers have been upgrading their formulations in order to improve weathering and waterproofing properties.

Primed products, silicones and urethanes, are performing similarly, confirming the tendency observed in the first set of products. This is a very interesting fact since urethanes are known to be susceptible to weathering. It can therefore be inferred that urethane manufacturers are trying to remedy that weakness by improving their formulations. Hybrids products are performing poorly again, indicating that there is a need for the industry to combine the best characteristics of silicones and urethanes.

The silicone and urethane filed specimens are performing well, as expected. In this case, urethanes are doing slightly better. On the other hand, hybrids are doing worse than in the first set of testing.

Figure 4.7 shows the comparison of failure percentage of second set specimens.

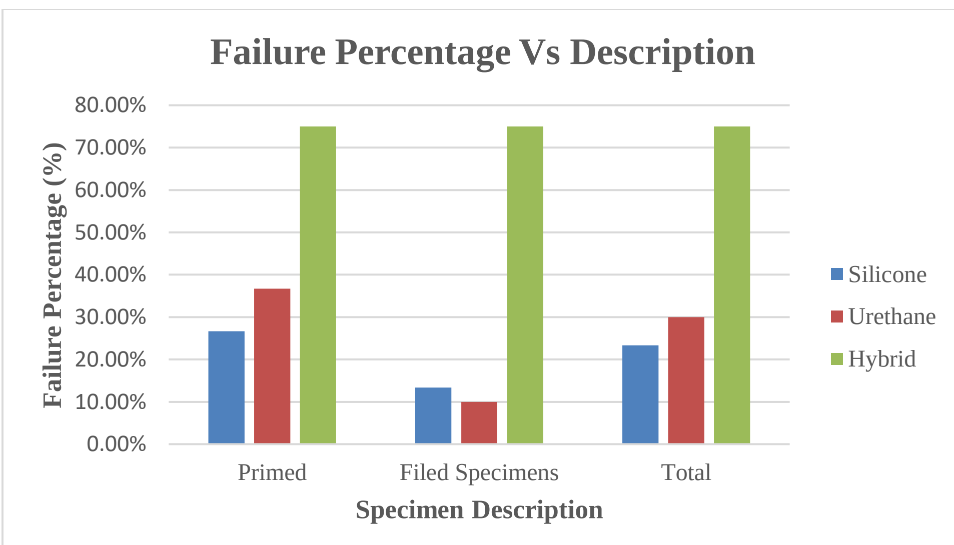

Figure 4.7: Failure Percentage of Second Set of Testing.

Lastly, the failure percentage of both SWRI validated and non-validated products has decreased substantially in this test compared to the first one, this is mainly due to the improvement of silicones' and urethanes' performances. Figure 4.8 shows the failure percentage of validated and non-validated products.

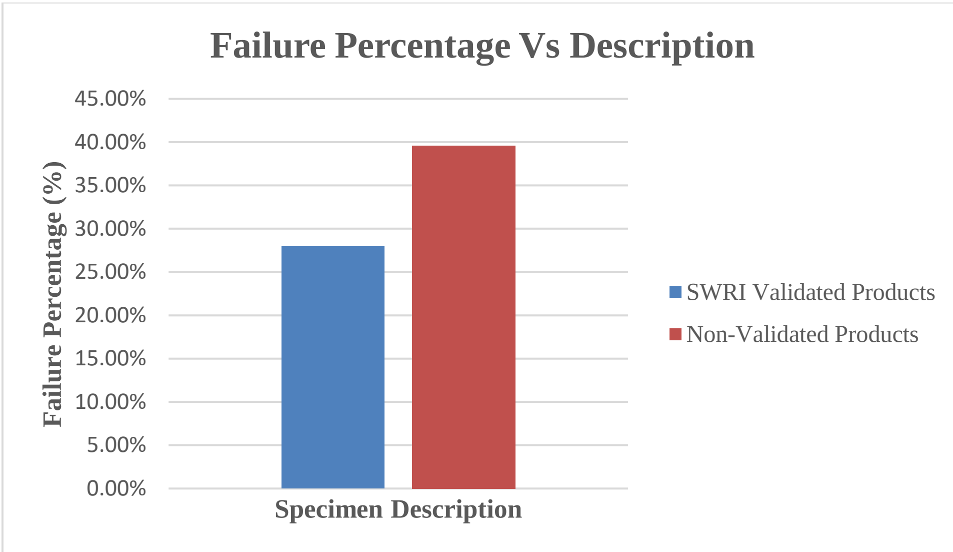

Figure 4.8: Failure Percentage of Validated and Non-validated Products – Second Set of Testing.

Several conclusions can be drawn at this point of the research concerning the different type of tested building sealants:

1. Silicones are the best performers; their performance is relatively similar whether or not primer is used.

2. Hybrids work better without using a primer. Their chemical composition allows them to take advantage of ambient conditions to increase their effectiveness.

3. Urethanes should be always primed in order to maximize their performance. In some cases, and depending on the product, they could perform better than silicones.

4. The validation from the SWRI serves as a good filter for products, but the difference with respect to non-validated products is not remarkable.

Chapter 5: Water Repellents

5.1. Introduction

Water repellents are commonly used on substrates such as concrete, clay brick, masonry, concrete blocks, stucco, and natural stone at the building envelope since there is a concern due to their high porosity and water absorption capacity. Water repellents are intended to be durable over time, while exposed to weathering and ultraviolet radiation.

For this purpose, two different types of water repellents have been developed, film formers and penetrants, which can be used depending on the requirements and ambient conditions.

Film formers (acrylics, urethanes, stearates, mineral waxes) create a layer over the substrate capable of bridging hairline cracks because of the large size of their molecules; this implies that film formers are directly affected by UV degradation. On the other hand, penetrants (silanes, siloxanes, siliconates, silicates, silicone resins, and RTU silicone rubber) do not cover the pores or cracks of the substrate since they have smaller molecules that allow them to penetrate and clog the pores from the inside. Also, they develop good vapor permeability and can last longer because they are not directly exposed to UV radiation.

This chapter presents the results of an ongoing test concerning the capability of these products to effectively minimize the absorption of water by terra-cotta clay saucers when cyclically (twice a year) tested. After the initial application of the product and the first cycle done by a previous student, two more cycles were conducted in order to have sufficient information to present significant takeaways in this chapter.

5.2. Background and Testing Standards

Five ASTM standards were considered for the test: the ASTM C642, *Standard Test Method for Density, Absorption, and Voids in Hardened Concrete*; the ASTM C67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*; the ASTM C140, *Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units*; the ASTM C97, *Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone*; and the ASTM D6532, *Standard Test Method for Evaluation of the Effect of Clear Water Repellent Treatments on Water Absorption of Hydraulic Cement Mortar Specimens*.

These standards establish similar procedures to test the absorption of construction materials such as CMU, clay, stone, mortar, and hardened concrete. However, they do not consider the performance of the water repellents exposed to ambient conditions (including temperature, rain, and UV radiation) as it would be throughout their service life.

The use of terra-cotta saucers was determined because of the homogeneity and relative constant properties of the material, regardless of different batches, which helps to have less variation in the obtained data at different stages of the test.

This test serves as real comparison criteria of the different types of water repellents, film formers or penetrants, and water-based or solvent-based, which were clearly explained by Gagnon (2016).

Furthermore, this document presents the analysis of the test results after the initial product application. Important trends are also noted.

5.3. Testing of Water Repellents

Following the test started by Gagnon (2016), where the initial application procedure was detailed, and the first round of test was performed, this document focuses on the effectiveness of all the tested products after the fourth round of testing.

Thirty-two different water repellent products, all penetrating (19 water-based and 13 solvent-based), have been tested. These products are representative of the market share and the various formulations used by manufacturers. A summary of the tested products is presented in Table 5.1 and the exposed specimens are shown in Figure 5.1.

Table 5.1: Classification of Tested Water Repellents.

Chemistry of the Water Repellent	**Quantity in this Test**
Silane	11
Siloxane	1
Siliconate	1
Silicone	1
Silicone Rubber	5
Silane/Siloxane	8
Silicate/Silane	1
Other	4
Total	32

Cyclic immersion tests are performed approximately every six months in accordance with the so-called six-month procedure presented below:

1. Remove the specimens from the rack. It is preferred to do that the first day preceded by "dry" days. If it rains for a short period of time, take the specimens from the rack and let them dry inside for a couple hours before starting with the test. The specimens should dry relatively quick at room temperature. If it rains for a long period of time, take the specimens from the rack, weigh them, and wait a couple hours at room temperature. After that time, weigh them again to evaluate if they have dried. If they have not, then postpone the test.

2. Weigh all the specimens in order to get their dry weight.

3. Conduct a RILEM test on every (A) specimen. Attach the RILEM tube to the side of the specimen that has been exposed to weather conditions. Use only the long RILEM tubes and fill them up to the mark 0ml. Record the readings from the RILEM tube every five (5) minutes from 0 to 20 minutes. If after that time, the specimen absorbs any water, continue the test up to 60 minutes, getting readings at 30 minutes and at 60 minutes. Weigh the specimens after the RILEM tube test in order to check the water absorption (water weight = 1g/ml). Note: To prevent air bubbles, it is recommended to have the tip of a plastic squeeze bottle in physical contact with the back of the tube while filling it until the zero mark. If there are air bubbles, the test should be repeated.

4. Dip the specimens in distilled water for 48+/-2 hours, placing every set of specimens with the same product applied in a plastic container (6Qt containers, fill them up to approximate 3-in. from the bottom). It means that specimens 1A, 1B, 1C, and 1D are placed in the same container.

5. After 48 hours, weigh the specimens again. Use a damp cloth to remove the excess of water on the surface before weighing them. (saturated surface dry = SSD).

6. Place the specimens on metal trays and apply some mist using a sprayer with distilled water and evaluate their beading ability.

7. Re-expose the A, B, C specimens of each product on the rack and store the specimen D.

Figure 5.1: Water Repellent Specimens.

5.4. Observations and Discussion about Water Repellents

The comparison of the performance of all the products was done based on the description of each product, based on the results obtained after the fourth test. A summary of the average effectiveness at the end of each round of testing is presented in Table 5.2.

Table 5.2: Average Effectiveness of Water-Repellent Products after Each Test.

Type of Water Repellent	Effectiveness 1st Test (%)		Effectiveness 2nd Test (%)		Effectiveness 3rd Test (%)		Effectiveness 4th Test (%)	
	Exposed	**Filed**	**Exposed**	**Filed**	**Exposed**	**Filed**	**Exposed**	**Filed**
Silane	82.88	75.53	89.59	87.79	90.25	90.86	91.43	92.24
Siloxane	92.46	91.37	89.60	91.98	89.23	92.54	90.58	93.17
Siliconate	6.59	8.71	38.79	54.23	40.47	79.95	21.62	85.59
Silicone	89.98	89.17	89.94	93.32	88.71	91.10	90.03	94.81
Silicone Rubber	50.01	49.53	88.62	89.34	89.53	90.98	88.78	93.33
Silane/Siloxane	76.77	76.09	81.01	86.47	81.49	91.43	81.50	92.05
Silicate/Silane	89.20	86.03	85.56	83.62	85.47	84.31	86.58	87.04
Other	23.70	23.61	33.99	41.71	37.78	68.15	38.19	73.26

It was found that the water repellent products on average improve their performance over time, except for the siliconate and "other" repellents. Siliconates have an average effectiveness of 26.87% for exposed specimens, and of 57.12% for filed specimens. The other repellents have an average of 33.42%, and 51.68% for exposed (specimens that are left outdoors) and filed specimens (specimens that are left indoors), respectively.

Furthermore, 75% of different types of water repellents have reached an effectiveness of at least of 80% at some point during the testing. This means that the probability of using an appropriate water repellent, taking into account the sample of 32 products, is quite favorable. Table 5.3 shows the total average effectiveness of all the products.

Table 5.3: Total Average Effectiveness of Water-Repellent Products after the Fourth Test.

Type of Water Repellent	Average Effectiveness (%)	
	Exposed	**Filed**
Silane	88.49	86.61
Siloxane	90.47	92.26
Siliconate	26.87	57.12
Silicone	89.66	92.10
Silicone Rubber	78.90	80.80
Silane/Siloxane	80.19	86.51
Silicate/Silane	86.70	85.25
Other	33.42	51.68

Generally, siloxanes, silicones, and silanes are the best performers with a total average effectiveness of 90.47%, 89.66%, and 88.49% for exposed specimens, and of 92.26%, 92.10%, and 86.61% for filed specimens. Next, in successive order, are silicates/silanes, silanes/siloxanes, and silicone rubber with a total average effectiveness of 86.70%, 80.19%, and 78.90% for exposed specimens.

In most cases, the performance has continued to increase over time. This is interesting because the expectation is that after approximately one and a half years, every applied product should have reached its maximum effectiveness. Another reason why the performance of the water repellents might be affected is weather conditions. This could be confirmed by comparing the results of exposed and filed specimens as evidenced in the bar graphs shown in Figures 5.2 and 5.3.

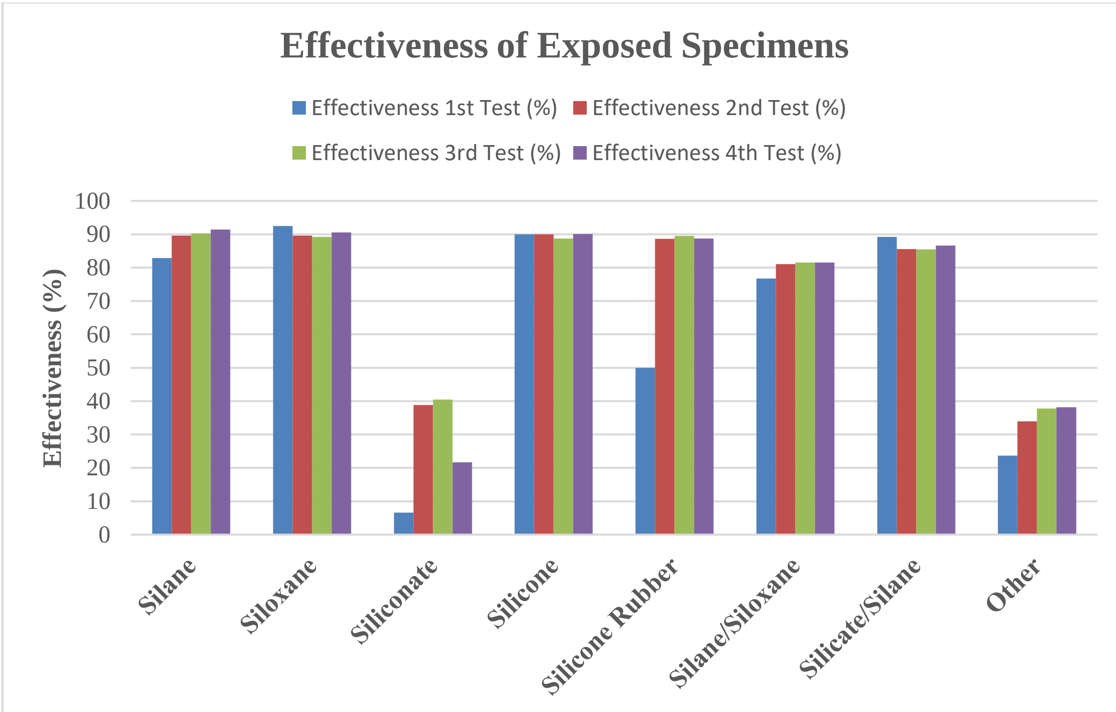

Figure 5.2: Effectiveness of Exposed Specimens after Each Test.

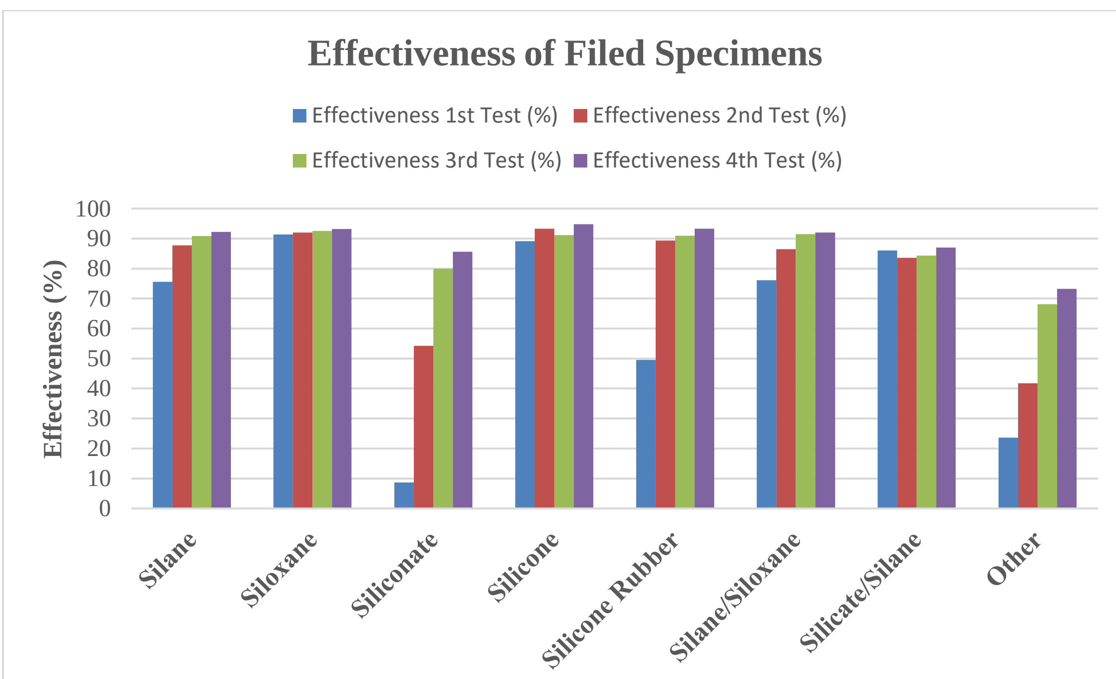

Figure 5.3: Effectiveness of Filed Specimens after Each Test.

Water repellents can also be classified as water based or solvent based. Table 5.4 shows the average effectiveness of the products regarding this classification.

Table 5.4: Average Effectiveness of Water-Based and Solvent Based Products After Each Test.

Type of Water Repellent	**Effectiveness 1st Test (%)**		**Effectiveness 2nd Test (%)**		**Effectiveness 3rd Test (%)**		**Effectiveness 4th Test (%)**	
	Exposed	**Filed**	**Exposed**	**Filed**	**Exposed**	**Filed**	**Exposed**	**Filed**
Water - Based	55.78	54.28	71.45	73.66	72.83	85.33	71.24	87.53
Solvent - Based	74.18	74.42	89.29	90.55	89.64	91.26	90.01	93.00

It was observed that water repellent products need time to develop their maximum effectiveness. For penetrating products, weather conditions and UV radiation mainly take longer to produce than the chemical reactions that yield complete water repellency. Also, prolonged exposure affects the effectiveness of water-based products as observed after the third test when the effectiveness of exposed specimens dropped slightly.

On average, solvent-based water repellents started with a relatively high effectiveness. During the same time, the efficiency was shown to be quite similar for exposed and filed specimens. It could be stated that they guarantee stability whether exposed to ambient conditions or not.

Solvent-based products are outperforming the water-based products. Their total average effectiveness is around 86% while water-based products' effectiveness is approximately 68%. Similarly, filed specimen effectiveness is 87.31% and 75.20%, respectively, as shown in Table 5.5.

Table 5.5: Total Average Effectiveness of Water-Based and Solvent Based Products Fourth Test.

Type of Water Repellent	**Average Effectiveness (%)**	
	Exposed	**Filed**
Water - Based	67.82	75.20
Solvent - Based	85.67	87.31

Figures 5.4 and 5.5 show the effectiveness of both types of water repellents after each round of testing.

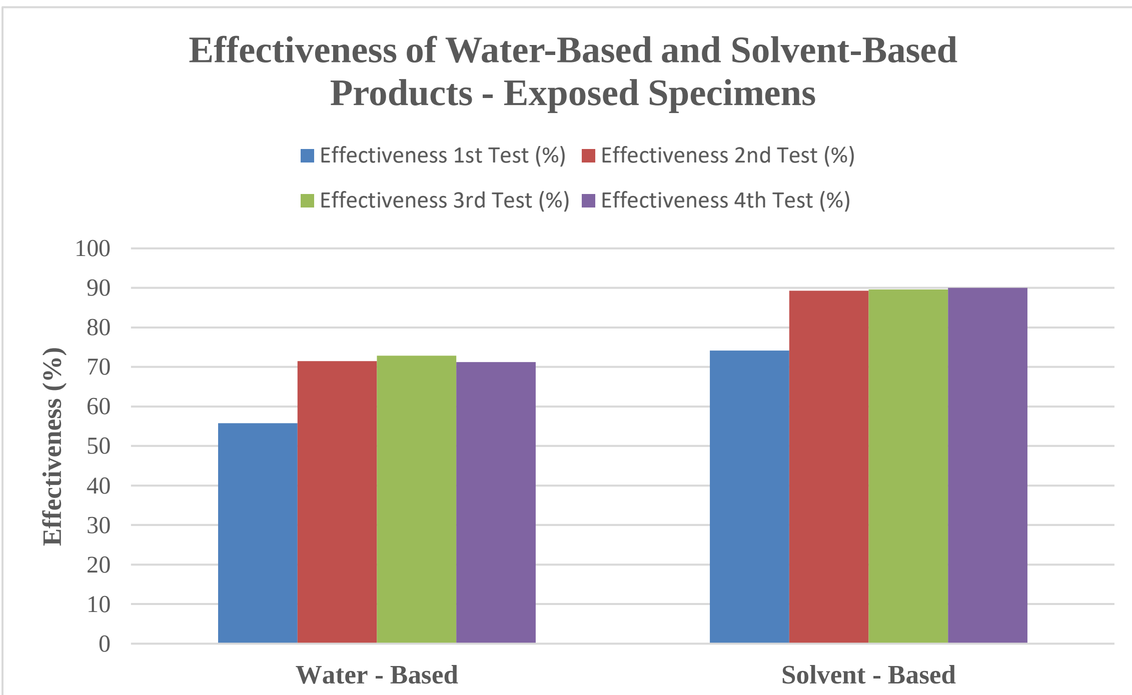

Figure 5.4: Effectiveness of Water-Based and Solvent Based Products – Exposed Specimens.

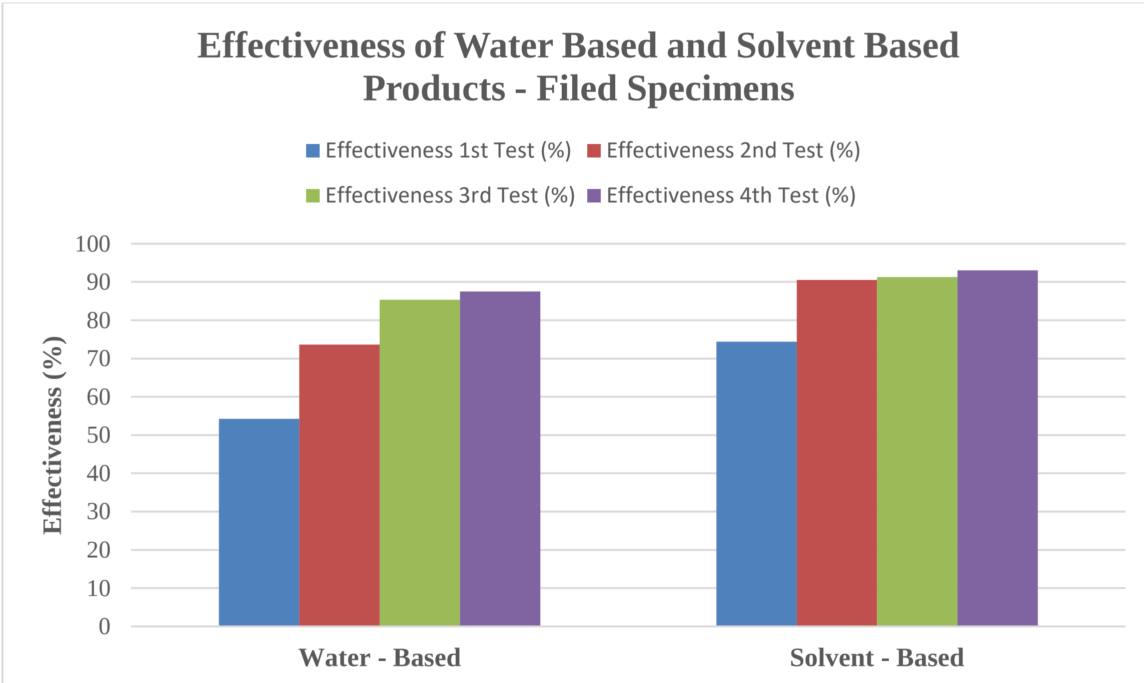

Figure 5.5: Effectiveness of Water-Based and Solvent Based Products – Filed Specimens.

It is unknown why water repellent products take more than a year to develop their maximum effectiveness, regardless their type. However, they have been performing better over time.

Based on the collected testing data, presented in Appendix 4, and the analysis presented before, it can be summarized that:

1. Curing time is different regarding each product. It could be weeks and even months. Some products need UV radiation to cure properly. There is no clear reason why water repellent products take that long to achieve their maximum effectiveness.

2. Siloxanes and Silicones are top two performers as well as solvent-based products. This means a siloxane solvent based penetrating water repellent could be used to get the most water repellency based on the results observed so far.

3. Stored specimens are likely to show more efficiency compared to the exposed specimens for some specific products. This could be because of the influence of UV exposure, rain, wind, temperature, and degradation, among others.

4. Some products, even after curing, do not reach 60% of effectiveness, especially the exposed specimens. On the other hand, stored specimens typically increase their effectiveness over time.

5. Some exposed products have better performance than stored specimens.

6. Some products perform better after the product application, and then the performance decays.

7. Some products have performed well since the beginning of the test (steady effectiveness over 85%).

8. The RILEM tube test is not a determinant indicator of the water repellency ability of these products, but provides a good reference for the short-term behavior.

9. Beading ability has no correlation to the effectiveness of water repellent products.

Chapter 6: Construction Tapes and Flashings

6.1. Introduction

Construction tapes and flashings are known for their capability to span gaps and handle details such as window opening perimeters and brick tie locations. They are usually part of a barrier system that does not allow water to go inside the building. For this reason, tapes should be properly installed to perform accordingly. On the other hand, if they are not reliable and durable enough, many issues could affect the correct performance of the entire system.

Due to the importance of tapes in a building envelope system, it is vital that the contractors feel confident using them, and that the manufacturers provide sufficient information (tests, material limitations, application instructions, and suitable primers, among others) about them in order to assure the correct usage of such products. Unfortunately, this information is not always available.

This research uses a shear adhesion test performed under weather conditions to evaluate the performance of representative tapes depending on the type of adhesive and the type of substrate. The objective of the test is to identify the suitability of specific tapes on different substrates that will ensure the proper functioning of the system over time. Two new substrates were added in the last year to the test that was started by the previous student. Also, new tapes and testing conditions were evaluated before the data analysis presented in the following pages.

6.2. Background and Testing Standards

The performance of construction tapes and flashings is intimately related to water-resistive barriers since together they constitute the waterproofing system of the building envelope. The International Building Code (IBC) and the International Energy

Conservation Code (IECC) both refer to tapes and flashings as materials used to prevent the flow of water to the inner side of the building or to re-conduct it to drainage systems by sealing seams, joints, and places where changes in geometry or materials are encountered.

The adhesion of tapes could be evaluated by performing a shear test, which can be done three simple ways. The first one is by applying an out-of-plane force, the second one by twisting, and the third one by applying an in-plane force. For this test, in-plane forces were initially considered because the majority of the standards available are based on this type of test. However, a test using out-of-plane forces will be performed to some specimens based on the standard ASTM D4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*, after this round of testing.

Also, the threshold established by the Revision 14 (June 2015) of the Air Barrier Association of America's "ABAA Process for Approval of Air Barrier Materials, Accessories and Assemblies." would be considered at the time of the test. This threshold consists of a pull-off adhesion of 110.3 kPa (16 psi). This out-of-plane test provides information about the properties of the tape, but not about the actual behavior of a tape under conditions commonly found in the field, where movement in plane is critical.

There are several testing standards that permits evaluation of the performance of tapes to develop the procedure for the ongoing test. The American Architectural Manufacturers Association (AAMA) in its 711-13 Standard considers a vertical mockup where tape samples are installed to mimic a wall situation exposed to different levels of temperature using primed and unprimed materials.

On the other hand, the standard ASTM D3654, *Standard Test Methods for Shear Adhesion of Pressure-Sensitive Tapes*, uses smaller samples installed on plywood substrate only with hanging weights installed at the bottom to induce failure.

None of the standards reviewed include outdoor exposure, which includes high solar radiation, wind, and rain, as additional factors to observe the durability of construction tapes and flashings.

6.3. Testing of Tapes

To define a testing procedure that considers exposure to weather conditions and does not affect the failure time of the samples, the ASTM D3654 Standard was modified including a bigger contact area (4-sq. in.). Additionally, the use of many different substrates such as plywood, OSB smooth and rough side, gypsum sheathing, integrated to sheathing WRB, EPS insulation, and tape over tape was permitted. Representative tapes of each type were selected to be tested on an outdoor rack erected at the exposure site at The Pickle Research Campus of The University of Texas at Austin. The elevation layout of the rack and the dimensions of each sample are shown in Figures 6.1 and 6.2, respectively.

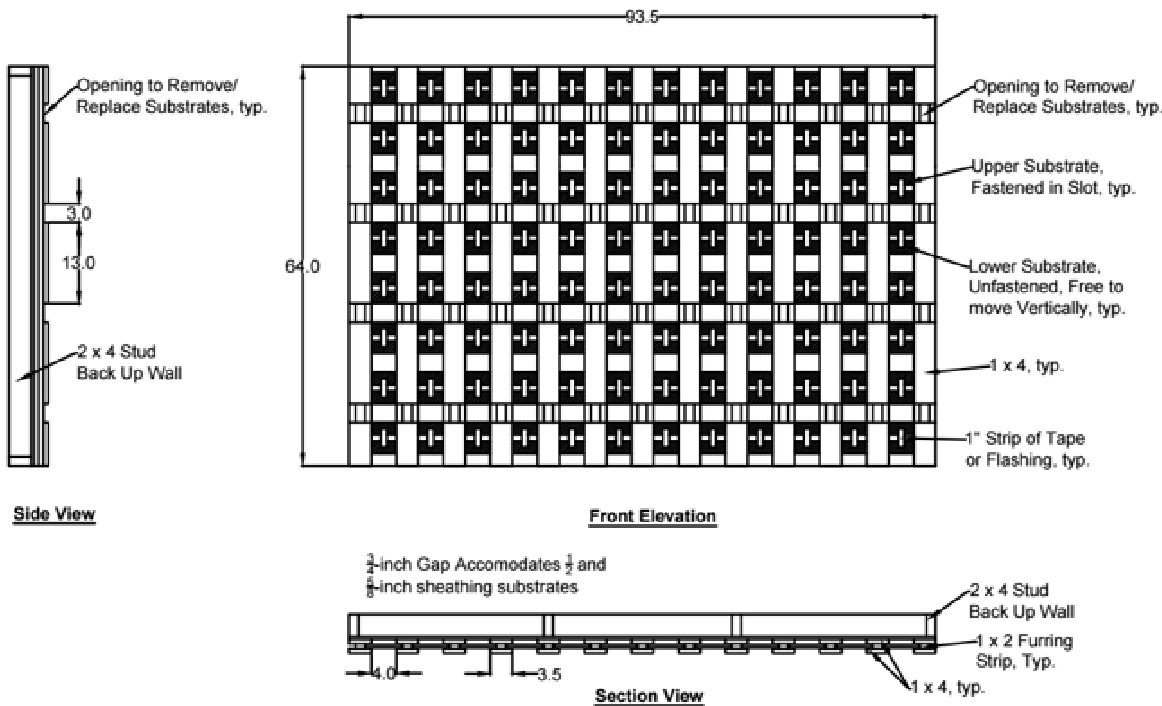

Figure 6.1: Elevation Layout Tape Testing Rack.

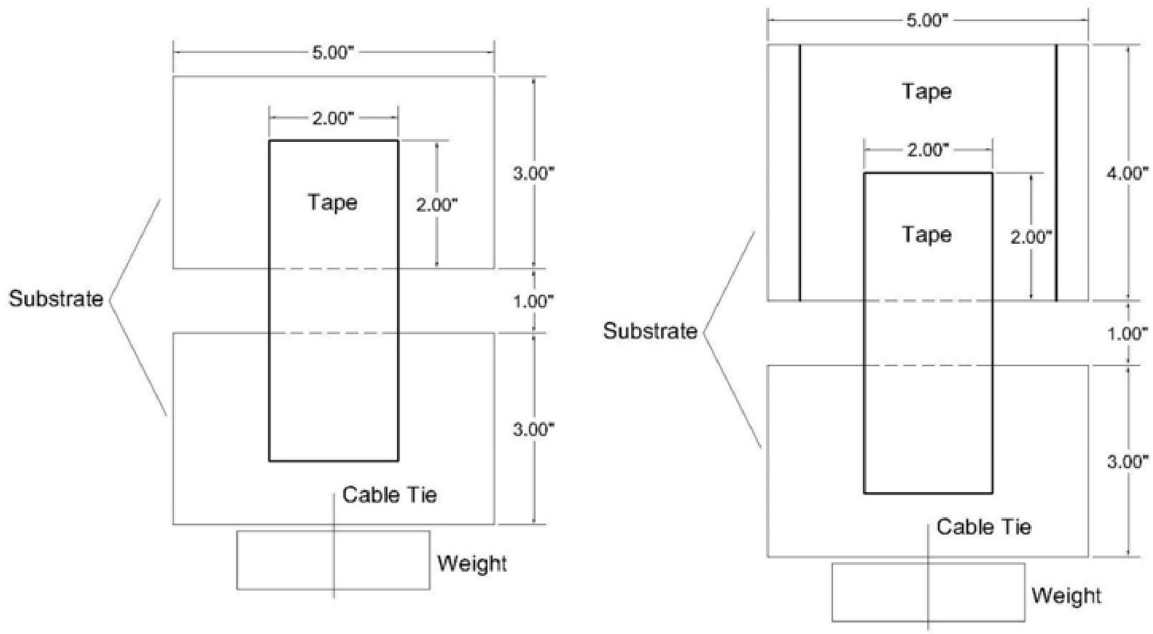

Figure 6.2: Typical Dimensions of Specimens.

The test procedure is as follows:

1. Select the tape to be tested according to the type of adhesive (acrylic, butyl, and modified asphalt).

2. Select the substrate to be used for the specimen (plywood, OSB smooth side, OSB rough side, integrated WRB sheathing, gypsum sheathing, EPS insulation, tape over tape).

3. Cut six (6) pieces of the selected substrate. Approximate dimensions: 3-in. x 5-in.

4. Cut one (1) strip of the selected tape. Approximate dimensions: 2-in. x 5-in. For each different tape, three strips shall be cut.

5. Apply the primer to the pieces of the substrate, if needed, and install the tape carefully setting a 4-sq. in. contact area between the tape and each piece of substrate.

6. An approximate total weight of 1lb. (including the bottom piece of substrate and the weight) shall be attached to the bottom piece of the substrate using a cable tie.

7. Define the waiting time (this is the time after the tape has been installed and before the sample is exposed on the rack) for each specimen. It could be no time, 12 hours, 24 hours, or 72 hours.

8. Hang the specimen on the rack and record the date and time of exposure.

9. Keep track of the specimens exposed on the rack to record the date and time of failure.

For this test, products of eight different manufacturers were used, distributed into 8 acrylic, 5 butyl, and 6 rubberized asphalt tapes. Figure 6.3 shows a photo of the rack.

Figure 6.3: Photo of the Tape Testing Rack.

Additionally, a qualitative test using strips of tapes is ongoing. In this test, the intention is to observe the effect of different weather conditions at the time of installation, taking into consideration that tapes can be installed after they have been stored at the job site. Figure 6.4 shows the two different sets of tapes used for this test.

Figure 6.4: Strips of Tapes Exposed on Integrated WRB Sheathing.

6.4. Observations and Discussion about Tapes

So far, tapes have been tested over six different substrates (plywood, OSB smooth side, OSB rough side, gypsum sheathing, integrated WRB sheathing, EPS insulation, and tape itself) for over 100,000 hours in total, and using 359 specimens.

After analyzing the collected test data, it was observed that there was a maximum time threshold. Once the tape reaches that threshold, it is very likely that tape will perform better over time.

This threshold was set to be 30 days after the exposure of the specimen on the rack. Currently, 95 specimens (26.4% percent) have reached the "cutoff" of 30 days without failure under loaded and exposed conditions. Table 6.1 summarizes the average failure time of all the types of adhesive as well as the different substrates, indicating the percentage of each that have reached the threshold.

Table 6.1: Average Time of Failure and Percentage of Reached Cutoff of Tested Tapes.

Adhesive	**Substrate**	**Average time of failure (days)**	**Reached cut-off**
Acrylic	Plywood	14.22	42.9%
	OSB Smooth	14.19	42.9%
	OSB Rough	10.54	33.3%
	Gypsum Sheathing	17.93	50.0%
	Integrated WRB	23.24	71.4%
	EPS Insulation	19.80	44.4%
	Tape over Tape	15.36	41.7%
Butyl	Plywood	11.11	20.0%
	OSB Smooth	7.74	6.7%
	OSB Rough	7.42	0.0%
	Gypsum Sheathing	13.06	20.0%
	Integrated WRB	-	-
	EPS Insulation	10.40	0.0%
	Tape over Tape	9.16	0.0%
Modified Asphalt	Plywood	7.11	20.0%
	OSB Smooth	4.14	6.7%
	OSB Rough	0.08	0.0%
	Gypsum Sheathing	7.68	13.3%
	Integrated WRB	-	-
	EPS Insulation	11.43	10.0%
	Tape over Tape	2.51	0.0%

From the observations to date, it is evident that acrylic tapes are the top performers while butyl tapes slightly outperform modified asphalt tapes. Figures 6.5 and 6.6 show a graphical comparison of all tested tapes.

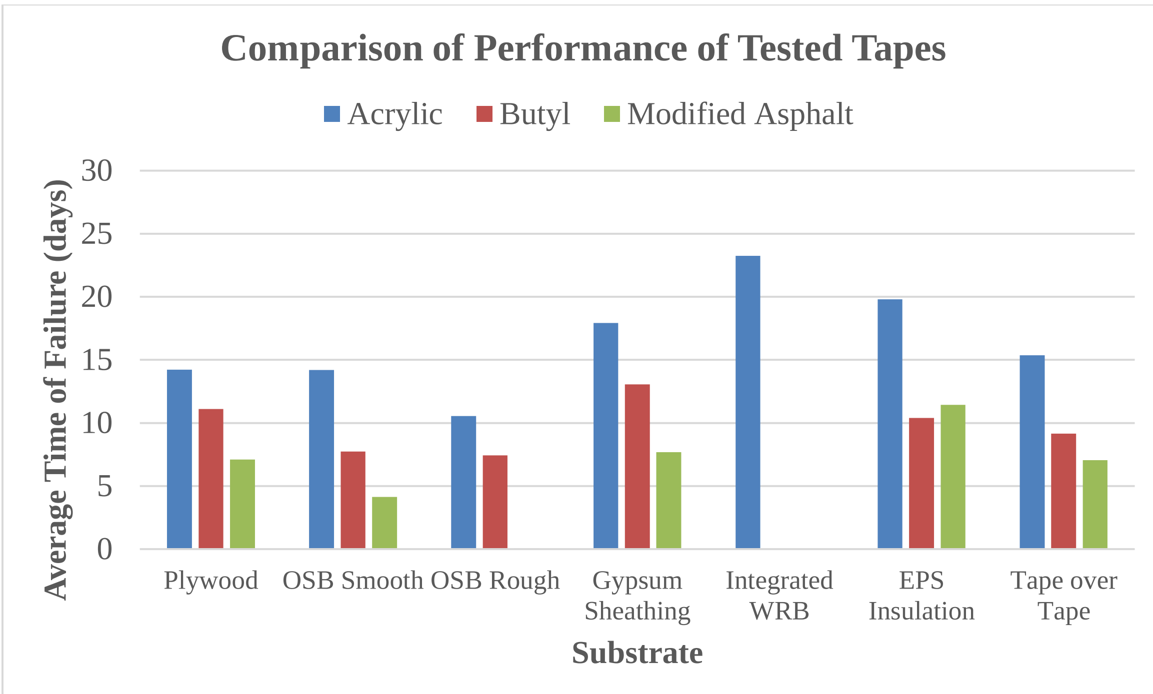

Figure 6.5: Average Failure Time of Tapes.

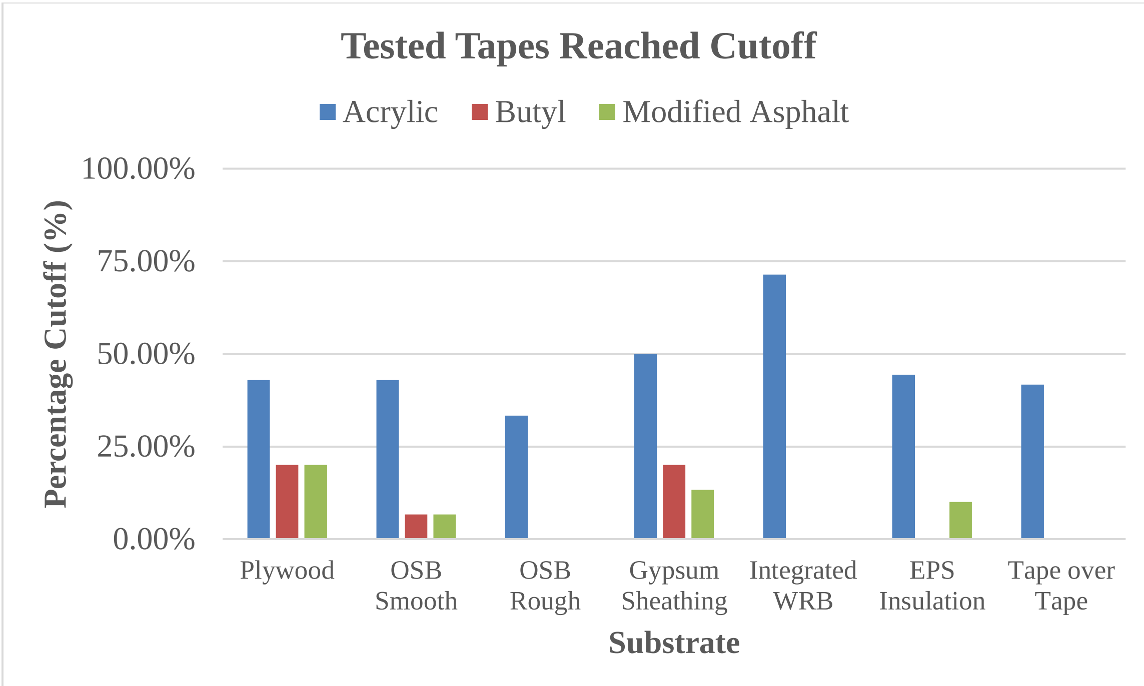

Figure 6.6: Percentage of Tapes That Reached the Threshold.

It was also possible to identify different types of failure modes with respect to the adhesive type and the substrate as presented below:

- Scrim slid over the adhesive vertically; this could be due to the combined effect of temperature, lack of bonding between the adhesive and the scrim, and the shear force applied by the hanging weight. This failure mode is shown in Figure 6.7.

Figure 6.7: Vertical Sliding of the Scrim.

- A strong bond between the adhesive and the substrate was not developed (Figure 6.8). As result of this, the failure could happen either at the bottom or the top section of the tape by sliding effect. This could be explained by the incompatibility of some adhesives with some substrates. The latter suggests that it is essential to select the type of tape regarding the substrate or vice versa.

Figure 6.8: Bonding Incompatibility Between the Adhesive and the Substrate.

- Combined failure mode; some parts of the adhesive remain attached to both the substrate and the scrim of the tape at the time of failure, as shown in Figure 6.9.

Figure 6.9: Combined Failure Mode.

- When tape over tape was tested, failure occurred at approximately the same number of times at the interface between the two pieces of tape as at the bottom part of the test assembly. Figure 6.10 shows this failure mode.

Figure 6.10: Failures Tape over Tape Scenario.

Some important trends were also observed regarding the performance of each type of tape over each substrate, which support the following statements:

- Overall, acrylic tapes had an average failure time of 17 days, while butyl tape average was 10 days. Lastly, the average of modified asphalt tapes was around 6 days.
- Acrylic tapes showed better performance on integrated to sheathing WRB, followed by EPS insulation, and gypsum sheathing with average failure times of 23, 20, and 18 days, respectively.

- Butyl tapes performed well on gypsum sheathing with an average failure time of 13 days.
- Modified Asphalt tapes performed the best on EPS insulation sheathing. The average failure time was 11 days.
- The average time of failure of modified asphalt tapes was considerably diminished when no primer was used. This fact confirms the recommendation of the manufacturers to use primer in order to get proper performance.
- The rough side of the OSB sheathing was the worst performing substrate with a total average failure time of 7 days.
- Bottom failure was more likely to happen than top failure in all cases, but when tape over tape case is analyzed, the behavior was similar. This suggests that manufacturers are still having some issues in getting proper adhesion between the carrier sheet and the adhesive, which explains the presence of a release liner in most of the tapes.
- Regardless the type of tape and substrate, every tape should be properly installed, carefully following the manufacturer's instructions. The most important ones include: rolling the tape, installing the tape in between the acceptable ambient temperature range, and use of primer.
- The performance of tapes could be affected by degradation over time when they are stored. This could lead to early signs of failure.

Chapter 7: Effect of Surfactants on Water Resistive Barriers

7.1. Introduction

Surfactants have been assumed to be the cause of failure of house wraps because of their ability to alter the surface energy of wraps and/or felts or the surface energy of water. No correlation has been proven between them and water leakage when stucco is used for cladding. Additionally, not much research has been conducted considering a real scenario where surfactants cause this failure mechanism.

The intent of the preliminary test described in this chapter is to perform a simple test using two different products known for having some surfactants as ingredients such as dish soap and pre-blended stucco mix. These surfactant-based products were used to evaluate the performance of three wraps commonly used in construction by the RILEM tube test.

After analyzing the results, a new test considering other variables such as UV degradation, weatherization, and time is presented to collect more data that could assist in the understanding of the real effect of surfactants on house wraps over their service life.

7.2. Background and Testing Standards

The surface-active contaminants, known as surfactants, are chemical compounds that can modify the surface energy of either the water or the housewrap or the building paper as stated in Lstiburek (2001). They can lower the surface energy of the water allowing the “wetting” of the housewrap or the building paper surface, or they can raise the surface energy of the housewrap or the building paper.

Surfactants can be found in soaps, detergents that lower the surface energy of water, and in water soluble extractives in wood such as tannins and wood sugars in redwood and cedar that affect the surface energy of the wraps and building papers. Surfactants can also be found as ingredients of paints and stucco. The most common surfactants found in these products are: dodecyl benzene sodium sulfonate (DBSS), as a major component of detergents; polyvinyl alcohol (PVA), as a surfactant for the formation of polymer encapsulated nanobeads; and polyoxyethylene monomethyl ether (POE), as a dispersant (one or more surfactants) in several products such as toothpaste.

Based on this hypothesis, several investigations have been conducted on this matter. Fisette (2001), ran a series of tests with soapy water and cedar-extract solution over some wraps and felts. A water column was set on top of two different types of wraps and one type of felt. The conclusions of this test were that the wraps were more affected by the soap than by the wood solution and that the felt was equally and largely affected by the two types of surfactants.

The Canada Mortgage and Housing Corporation (CMHC) in its Research Highlights (August 2004) states that OSB and stucco can leach out some chemicals that represent a hazard to the air barrier system, especially in maintenance of some siding systems where pressure-spray washing can cause these compounds to get in contact with the wraps and/or felts. The principal conclusion states:

A very significant effect of surfactants (such as soap) on surface tension and kinematics was found. On the other hand, the soluble parts of wood extracts from some OSB materials were found to have a relatively small effect on the properties of pore water.

Holladay (2000), also says that the surfactants have the potential to degrade a plastic housewrap’s and asphalt felt´s water resistance.

Due to this, several recommendations have been made to avoid the known effects of surfactants on wraps and felts such as back-priming the wood sheathing and providing a drainage space between the stucco and the building paper or house wrap to control liquid phase water penetration. The latter can be achieved by installing two layers of building paper under the stucco.

Despite these tests having partially confirmed the initial hypothesis, the intent of this research is to mimic the real conditions that could lead to the worsening of the wrap performance because of surfactants.

7.3. Testing of Surfactants

A preliminary test using the RILEM tube was conducted to evaluate different scenarios where surfactants could be involved in practice. Also, other standard scenarios that could serve as a reference were considered when analyzing the performance of the house wrap. The test consists of a 60-min. RILEM tube test using the following liquids:

- Distilled water only.
- Distilled water and pre-blended stucco mix.
- Distilled water and dish soap (2% Volume).
- Distilled water, pre-blended stucco mix, and SRA (shrinkage reducing admixture).
- Distilled water and stucco mix obtained from a job site.

With respect to the wraps used for this test, the following classification was defined:

- Wrap 1: Wrap used for commercial buildings. A new roll.
- Wrap 2: Wrap used for residential buildings obtained from a building where water infiltration was observed.
- Wrap 3: Wrap used for residential building new from the roll. Wrap 2 is the same as Wrap 3, but after years of use.

The main purpose of this preliminary test was to observe the behavior of each type of wrap after putting it in contact with surfactants, especially the wrap that was obtained from a building where the water went through the wrap with no apparent damage and/or improper installation of the wrap. Each type of wrap was installed on a piece of plywood, where a horizontally attached RILEM tube was filled with the specified liquid, taking measurements of the drop in the water level at 5, 10, 15, 20, 30, and 60 minutes. All the data obtained from the RILEM tube were in milliliters. Also, each scenario was repeated at least twice.

7.4. Observations and Discussion about Surfactants

The results of the preliminary test are summarized in Table 7.1:

Table 7.1: Preliminary Test Results.

Case	**Description**	**RILEM Tube Readings in minutes (ml)**					
		5	**10**	**15**	**20**	**30**	**60**
1	Wrap 1 + Distilled Water	0.0	0.1	0.1	0.2	0.2	0.3
2	Wrap 1 + Distilled Water + Pre-blended Stucco Mix	0.0	0.1	0.1	0.1	0.2	0.2
3	Wrap 1 + Distilled Water + Dish Soap (2% Volume)	0.0	0.1	0.1	0.2	0.2	0.3
4	Wrap 1 + Distilled Water + Pre-blended Stucco Mix + SRA	0.0	0.1	0.1	0.1	0.2	0.2
5	Wrap 2 + Distilled Water	0.3	0.4	0.7	0.9	1.3	2.8
6	Wrap 2 + Distilled Water + Dish Soap (2% Volume)	0.4	0.8	1.2	1.5	1.9	3.1
7	Wrap 2 + Distilled Water + Pre-blended Stucco Mix	0.3	0.5	0.7	0.9	1.4	2.5
8	Wrap 3 + Distilled Water	0.0	0.1	0.1	0.2	0.2	0.2
9	Wrap 3 + Distilled Water + Dish Soap (2% Volume)	0.1	0.2	0.3	0.3	0.5	0.5
10	Wrap 3 + Distilled Water + Pre-blended Stucco Mix	0.1	0.2	0.2	0.2	0.2	0.3

Table 7.1: Continued

11	Wrap 3 + Distilled Water + Stucco Mix from Job Site	0.1	0.1	0.2	0.2	0.2	0.3

In cases 1, 2, 4, 8, 9, and 10 no water was noticed below the wrap after the test. On the contrary, water was noticed below the wrap in cases 3, 5, 6, and 7. Figures 7.1 and 7.2 show different test scenarios.

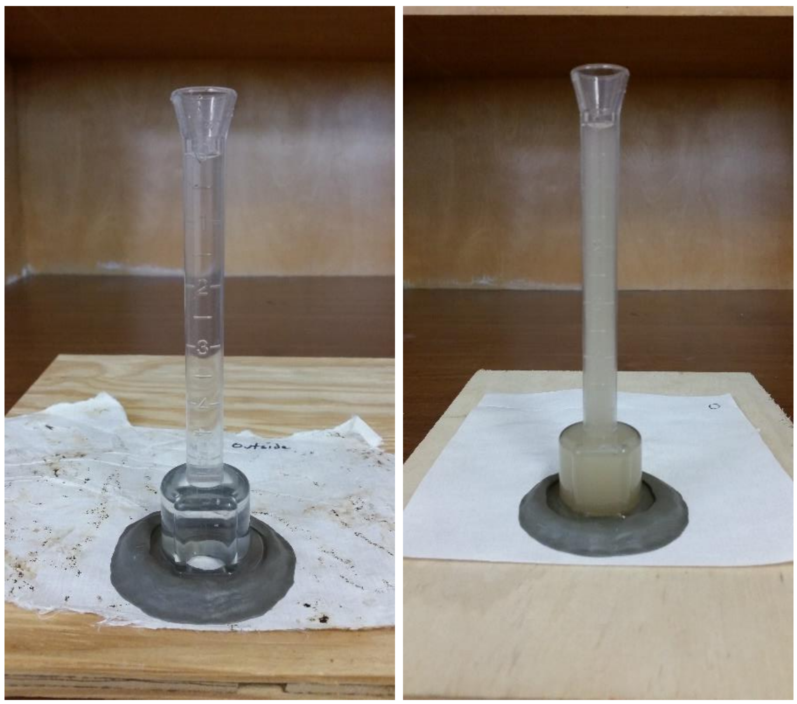

Figure 7.1: RILEM Tube Testing.

Figure 7.2: More RILEM Tube Testing.

The average results are shown in Figure 7.3:

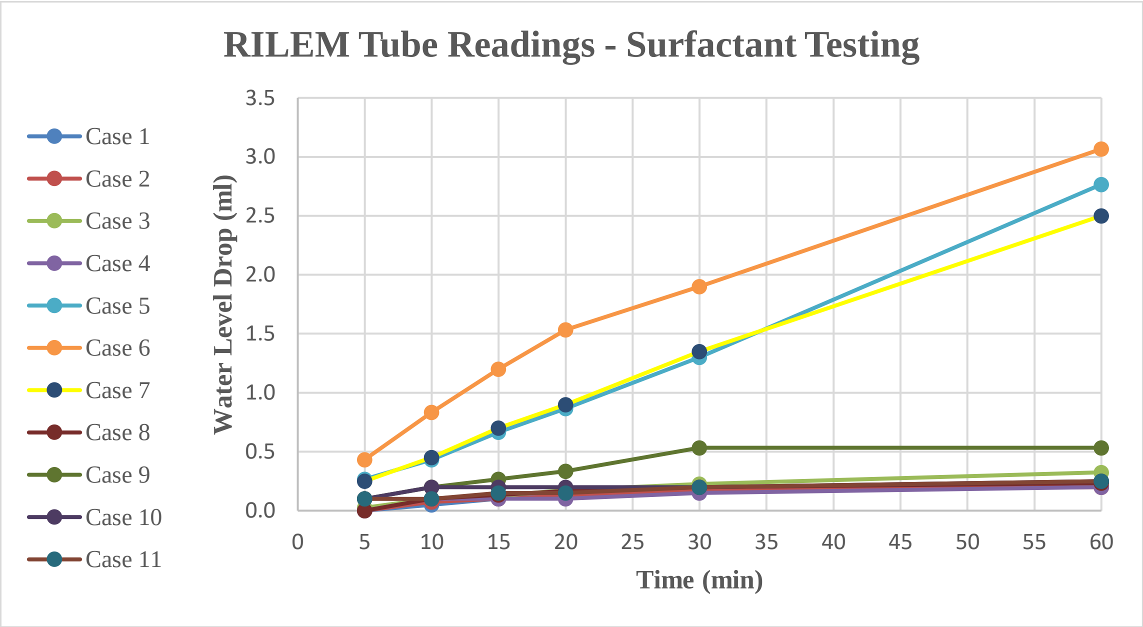

Figure 7.3: RILEM Tube Test Readings.

After analyzing the collected information, the following conclusions are drawn:

- Cases where wrap 2 was utilized (5, 6, and 7) were the most critical. Loss of water from the RILEM tube was at least 5 times more than for the other cases where wraps 1 and 3 were used.
- The two different types of stucco mixes used for this test yielded no different results and showed no adverse effect on the performance of each tested wrap.
- The dish soap caused water to go through the wrap, but when wraps 1 and 3 were used, the amount of water that penetrated was less than the amount of water that went through the wrap 2.
- When only distilled water was used (cases 1, 5, and 8), it was expected that the performance of the wrap would have been similar. This was not true for case 5, which did even worse than case 7 (distilled water + pre-blended stucco mix).
- The behavior of wraps 1 and 3 is similar, except for the case when dish soap was used (cases 3 and 9, respectively). It is known that the standards for commercial buildings are stricter than for residential buildings. The latter could be a reason why the effect of surfactants found in soaps is slightly higher on residential wrap than on commercial wrap.
- After analyzing case 11, where a sample of stucco from the job site was combined with water and a new piece of residential wrap were used, it was observed that no significant difference was found between the stucco mixes used for this test. This

is relevant because the stucco from the job site may not be the cause of the bad performance of the wrap.

Based on the latter observations, it was concluded that the poor performance of the wrap at the job site was not a direct consequence of surfactants. Instead, it may be a combination of several other factors that could certainly include surfactants.

To support this hypothesis, another RILEM tube test was performed on one of the exposed mockups that was built using the same type of wrap for residential buildings (Wrap 2) for the water-resistive barrier test (Figure 7.4). The RILEM tube test was performed on the covered part as well as on the uncovered part that had been overexposed to UV radiation for several years. A summary of the average readings is presented in Table 7.2.

Table 7.2: RILEM Tube Test on Wrap 2 Mockup.

Case	Description	RILEM Tube Readings in minutes (ml)					
		5	10	15	20	30	60
12	Top + Distilled Water	0.2	0.2	0.2	0.3	0.3	0.4
13	Bottom + Distilled Water	0.2	0.3	0.3	0.3	0.4	0.5

The performance of the wrap was similar to case 9. This time, only distilled water was used. Furthermore, it is interesting to note that the worsening performance of the wrap was caused mainly by overexposure to UV radiation in one case, and pure exposure to ambient conditions in the other case. This result is aligned with the first test, suggesting that the poor performance of wraps observed at the job site is the result of a combination of harmful factors such as surfactants and degradation.

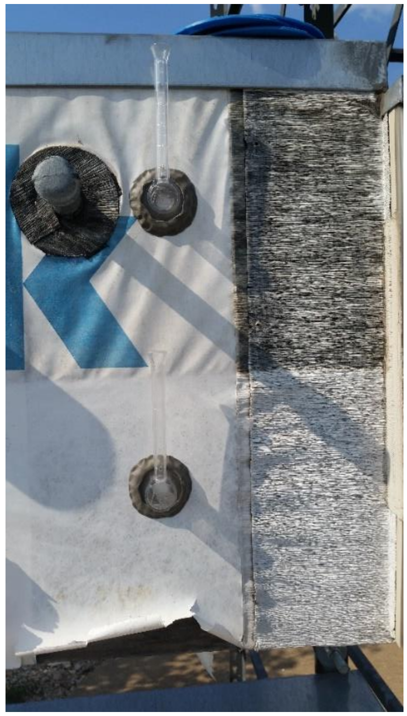

Figure 7.4: RILEM Tube Test on Wrap 2 Mockup.

Despite these results, other pieces of Wrap 2 were obtained from different locations at the job site, and the RILEM tube test was performed again just using distilled water. The results are presented in Table 7.3:

Table 7.3: RILEM Tube Test on other Pieces of Wrap 2 Obtained from the Job Site.

Case	**Description**	**RILEM Tube Readings in minutes (ml)**					
		5	**10**	**15**	**20**	**30**	**60**
14	Wrap 2 + Distilled Water (Other Pieces)	0.1	0.2	0.2	0.2	0.2	0.3

Unexpectedly, these new results contradict the initial hypothesis, and the performance of the pieces of Wrap 2 is similar to the performance of the Wrap 3. This could be an indication that the failure mechanisms of the wrap are happening independently, depending on the location where they were installed. Due to the latter, the initial hypothesis is not discarded at all, and it is paramount to find a relationship between these variables in the observed bad performance of the wrap.

A new testing procedure is being developed considering both the degradation of the wrap caused by weather conditions and the potential effect of surfactants. The long-term test consists of the following:

- Cases. Two cases have been considered for this test. In one case, the specimens are prepared using OSB as sheathing, one layer of wrap and one layer of felt as WRB, metal lath and stucco without admixtures (shrinkage reducing admixture). The other case would be exactly the same but with admixtures.
- Samples. Two mock-ups 2-ft x 3-ft to be exposed (oriented vertically) and one 1-ft x 1-ft to be filed. Stucco thickness: ⅞- in. after 3 coats.
- Temperature of materials: 65 °F – 75 °F (18 °C – 24 °C). All proportion of materials to be done by mass. Water and liquids could be done by either mass or volume.
- Mix the mortars following the ASTM C305, *Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency*. The plaster proportions are given as:

  Scratch coat: 1:2:9 ratio of portland cement, masonry cement, and sand.
  Brown Coat: 1:2:10.5 ratio of portland cement, masonry cement, and sand.
  Finish Coat: 1:2:6 ratio of portland cement, masonry cement, and sand.

Elevation and section views of the proposed specimens are shown in Figures 7.5 and 7.6, respectively.

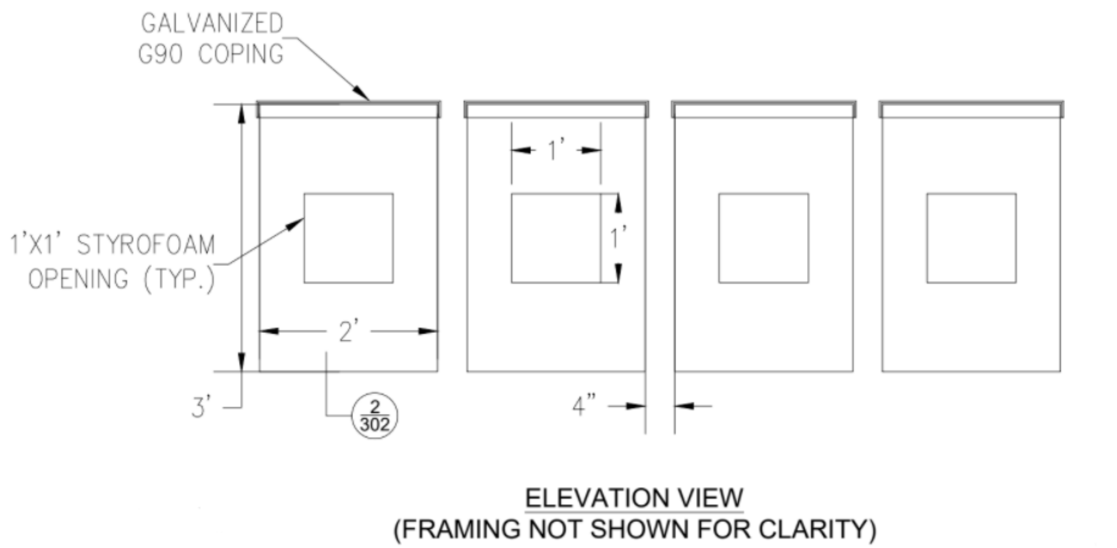

Figure 7.5: Elevation View of the Proposed Specimens.

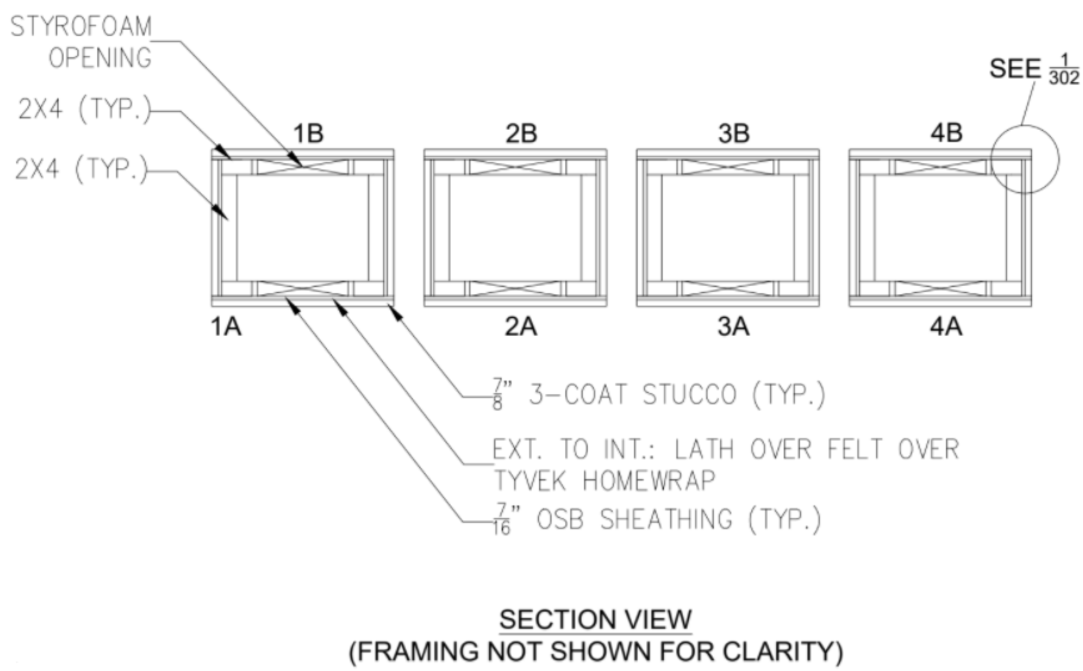

Figure 7.6: Section View of the Proposed Specimens.

- Curing. Apply the scratch coat. After it dries, apply the brown coat, then cure two days and apply the finish coat eight days after the initial application.

From ASTM C926 X.1.5.2:

Moist curing is accomplished by applying a fine fog spray of water as frequently as required, generally twice daily in the morning and evening. Care must be exercised to avoid erosion damage to Portland cement-based plaster surfaces. Except for severe drying conditions, the wetting of finish coat should be avoided, that is, wet the base coat prior to application of the finish coat.

- Time of exposure. This is a long-term test. The specimens will be installed on the rack facing south to get the maximum solar exposure. Observations will be made periodically. The status of the wrap will be observed at the back of the mockup.
- The maximum allowed number of staples/area of lath ratio is determined by ASTM C1063, *Standard Specification for Installation of Lathing and Furring to Receive Interior and Exterior Portland Cement-Based Plaster* Section 7.9.2. where for wood framing and sheathing on wood framing respectively says, use 11 gauge 1-1/2-in. length, 7/16-in. head nails (roofing nails 4d 1-1/2-in. x 1/4 head), and use 14 gauge, 1-1/2-in. leg, 3/4-in. crown staples.

With respect to the fastener spacing, the standard states that the spacing of nails, staples or screws is not more than 7-in. on center along the framing member (horizontal or vertical).

Summarizing, the categories and properties of the specimens are shown in the Tables 7.4, 7.5, and 7.6:

Table 7.4: Specimens Location and Categories.

Specimen location	Specimen Categories	
	with admixture	**without admixture**
Outside	1A: 2-ft x 3-ft	2A: 2-ft x 3-ft
Outside	1B: 2-ft x 3-ft	2B: 2-ft x 3-ft
Inside	1C: 1-ft x1-ft	2C: 1-ft x1-ft
• Same number of staples per area in all six specimens • Same thickness of stucco in all six specimens		

Additionally, to increase the degradation process, exposed specimens are also divided by having good and bad drainage.

Table 7.5: Exposed Specimens Characteristics.

Specimen IDs	1A/B	2A/B	3A/B	4A/B
Drainage	Good	Good	Bad	Bad
SRA	No	Yes	No	Yes

Table 7.6: Filed Specimens Characteristics.

Specimen IDs	1C	2C
Drainage	Good	Good
SRA	No	Yes

Following, schemes showing good and bad drainage for sill and jambs are shown in Figures 7.7, 7.8, 7.9, and 7.10:

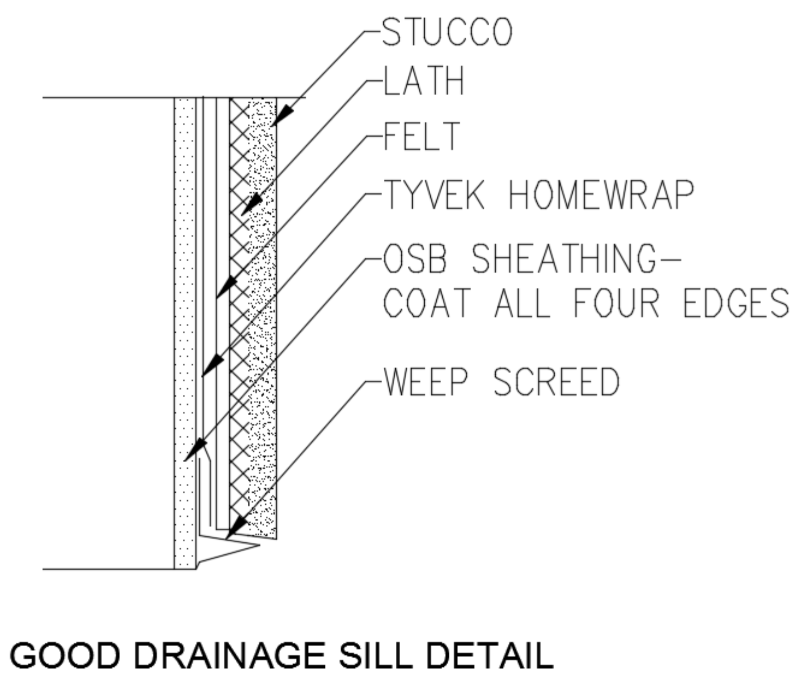

Figure 7.7: Good Drainage Sill Detail.

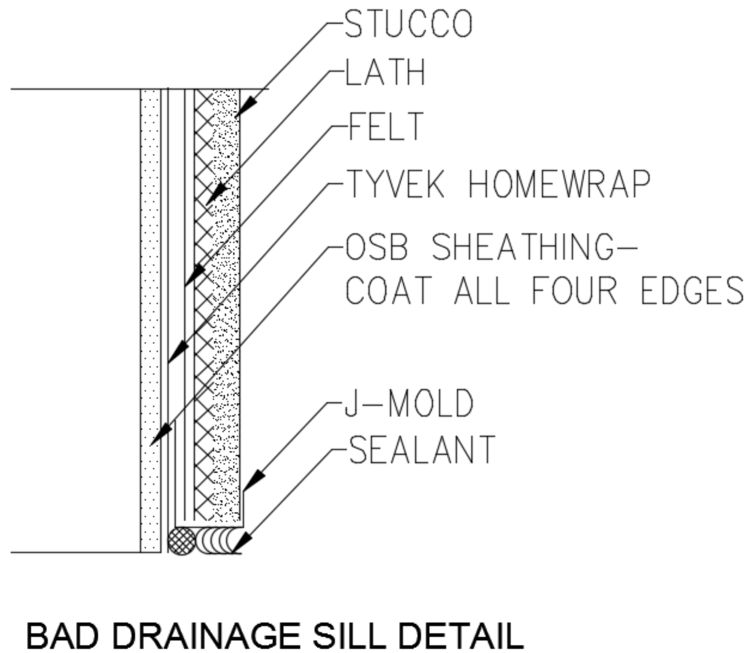

Figure 7.8: Bad Drainage Sill Detail.

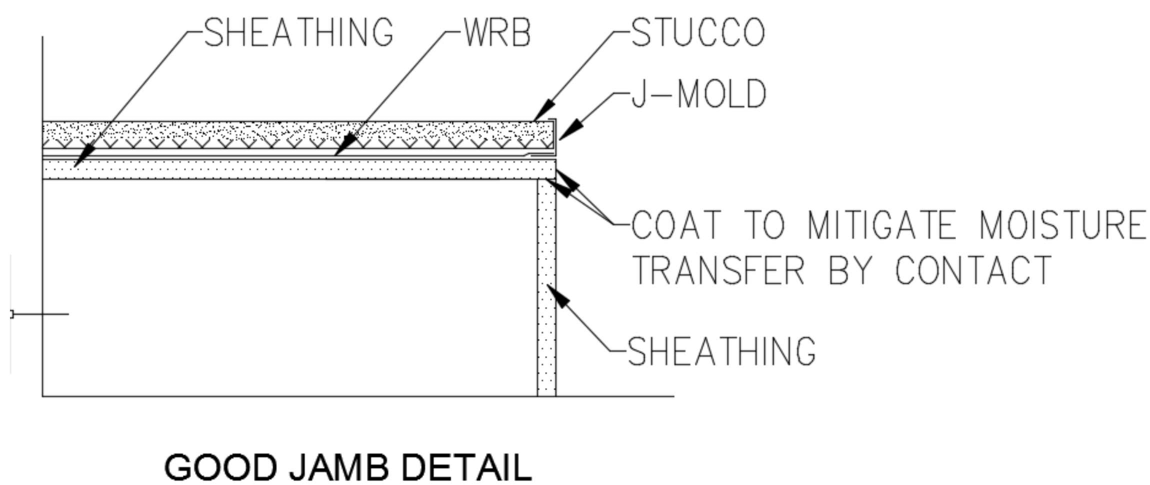

Figure 7.9: Good Jamb Detail.

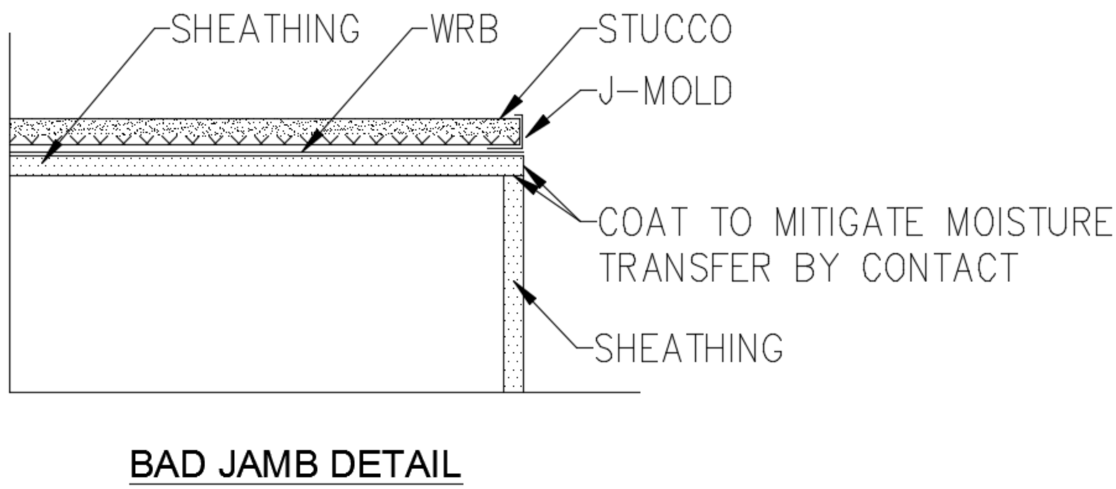

Figure 7.10: Bad Jamb Detail.

Also, as a part of the induced degradation process, water will be sprayed on the surface of the specimens on a regular basis (at least three times a week).

After exposing all the specimens, RILEM tube tests will be performed monthly on the outside and inside specimens to collect data for comparison purposes. Furthermore, observations of the wrap of each mockup will be made from the back side of the mockup to carefully follow the degradation process if that is the case.

It is expected that important takeaways could be stated regarding the role of surfactants on the actual performance of the wraps.

Chapter 8: Conclusions

The industry of building envelope materials is broad and is continuously expanding. As such, it is imperative that more careful attention is paid to the quality and performance of the increasing number of manufacturers' products available on the market on a daily basis. The sole objective of this relies on the fact that it is extremely difficult to control the manufacturing process and test all the different products. It is also true that many efforts have been made in order to tackle this growing issue, including the creation and modification of standards based on the development of new techniques and products; the creation of organization and institutes dedicated to provide minimum standards and acceptance criteria for specific products; and as in this case, the creation of laboratories in which the purpose is to test and observe the behavior and performance of building envelope products when exposed and overexposed to actual field conditions.

After presenting, discussing, and analyzing the results obtained by the sets of material testing presented above, the very first conclusion that can be drawn is that there is still a lot to learn about building envelope materials' behavior. Additionally, the understanding of what actually happens presents an outstanding opportunity to improve formulations. This also provides a good source of factual information for all users, especially manufacturers, by allowing them to evaluate their manufacturing process, and to identify weak points. This information could help them improve the quality of their products.

In the case of stucco, its behavior remains unpredictable due to the combination of several aspects, such as temperature, shrinkage, moisture content, aspect ratio, and components like metal lath, construction joints, and expansion joints. As a consequence of this, and to make the most of their key properties, it is almost mandatory to follow all the recommendations and specifications as well as to use high qualified workmanship to minimize potential issues.

With respect to the water-resistive barriers, each type of existing barrier has its own pros and cons, and for this reason, they should be addressed properly. Temperature changes and UV radiation play an important role, mostly when related to allowable exposure rate. Also, penetrations resulting from the installation of pipes, brick ties, metal lath, and the barrier itself could become potential failure points of the entire system, as was demonstrated by the nail sealability test, and the test performed on the integrated WRB sheet.

Building sealant fabricators have been progressively trying to integrate the best qualities of silicones and urethanes, but thus far, without great success. Hybrid sealants have become the new target of the industry, and there is a long way to go; meanwhile, silicones and urethanes share a greater portion of the market share. This is a fact that is confirmed by the results of this ongoing test in which silicone sealants are the top performers, followed closely by urethanes, and lastly by hybrids. It is worth mentioning that, with the exception of hybrids, use of a primer is vital to achieve the desired efficiency of sealants.

All the water repellent products, excepting the classified as siliconates and others, have yielded effectiveness values over 75% after four consecutive tests, which is indistinguishable if exposed or filed specimens are evaluated. Moreover, the performance of solvent-based products is slightly better than the water-based products. As an interesting fact, most of the products have been showing an increased effectiveness over time; this is surprising since it is expected that the maximum effectiveness of these type of products would be reached in less time.

The newest adhesive type developed for construction tapes and flashings, acrylic, is showing the best results when used with all the substrates, confirming why it has the biggest portion of the market share. Following the acrylic adhesive, butyl and modified asphalt adhesives constitute a special direct competition, with a marginal advantage for the butyl adhesive over the modified asphalt. It is noteworthy that even though acrylic tapes are the best performers, it does not mean that all the acrylic tapes available on the market are equally good.

The effects of surfactants on the behavior of stucco cladding over time still lack convincing evidence; it was noted that they decrease the efficiency of the wrap but not to an extent that can cause serious concerns, such as those noticed in the field. The results of the preliminary tests shown in this document lead to the arrangement of a long-term test which could lead to a better understanding of the entire system.

Finally, more effort is needed from everyone in the industry to consistently improve testing standards, production processes, installation skills, and developing specifications. More testing should be done, including weathering as a key factor, which, would result in improved performance of products.

Appendix 1 – Stucco Panel Readings

Date/Time	10/19/2016 5:15 PM			10/20/2016 2:00 PM				10/21/2016 2:00 PM			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.289	3.294	3.292	3.296	3.296	3.296	0.004	3.302	3.306	3.304	0.013
CJ-SL2	3.089	3.095	3.092	3.107	3.107	3.107	0.015	3.116	3.118	3.117	0.025
CJ-SL3	3.089	3.087	3.088	3.087	3.091	3.089	0.001	3.102	3.102	3.102	0.014
CJ-SR1	2.629	2.640	2.635	2.645	2.647	2.646	0.011	2.652	2.652	2.652	0.018
CJ-SR2	2.519	2.517	2.518	2.525	2.526	2.526	0.008	2.531	2.529	2.530	0.012
CJ-SR3	3.147	3.156	3.152	3.165	3.162	3.164	0.012	3.169	3.170	3.170	0.018
CJ-CL1	3.014	3.018	3.016	3.027	3.024	3.026	0.010	3.032	3.028	3.030	0.014
CJ-CL2	3.177	3.181	3.179	3.195	3.195	3.195	0.016	3.205	3.204	3.205	0.026
CJ-CL3	2.852	2.856	2.854	2.869	2.867	2.868	0.014	2.878	2.877	2.878	0.023
CJ-CR1	3.394	3.399	3.397	3.406	3.408	3.407	0.011	3.414	3.410	3.412	0.015
CJ-CR2	3.279	3.289	3.284	3.296	3.300	3.298	0.014	3.306	3.305	3.306	0.022
CJ-CR3	3.474	3.474	3.474	3.477	3.480	3.479	0.004	3.490	3.488	3.489	0.015
CJ-UL1	2.983	2.991	2.987	2.994	2.993	2.994	0.006	3.003	3.008	3.006	0.019
CJ-UL2	3.508	3.504	3.506	3.510	3.511	3.511	0.004	3.519	3.518	3.519	0.012
CJ-UL3	2.822	2.830	2.826	2.837	2.837	2.837	0.011	2.856	2.851	2.854	0.027
CJ-UR1	2.918	2.915	2.917	2.926	2.928	2.927	0.011	2.929	2.930	2.930	0.013
CJ-UR2	3.980	3.980	3.980	3.988	3.991	3.990	0.010	3.993	3.994	3.994	0.014
CJ-UR3	3.514	3.523	3.519	3.522	3.522	3.522	0.003	3.528	3.524	3.526	0.007

Date/Time	10/24/2016 10:00 AM				10/26/2016 10:00 AM			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.305	3.309	3.307	0.016	3.308	3.307	3.308	0.016
CJ-SL2	3.117	3.119	3.118	0.026	3.124	3.124	3.124	0.032
CJ-SL3	3.102	3.101	3.102	0.013	3.107	3.106	3.107	0.019
CJ-SR1	2.652	2.654	2.653	0.019	2.656	2.658	2.657	0.023
CJ-SR2	2.538	2.533	2.536	0.018	2.547	2.541	2.544	0.026
CJ-SR3	3.175	3.175	3.175	0.023	3.179	3.179	3.179	0.027
CJ-CL1	3.028	3.029	3.029	0.013	3.035	3.035	3.035	0.019
CJ-CL2	3.204	3.208	3.206	0.027	3.211	3.211	3.211	0.032
CJ-CL3	2.880	2.881	2.881	0.026	2.886	2.886	2.886	0.032
CJ-CR1	3.414	3.413	3.414	0.017	3.418	3.419	3.419	0.022
CJ-CR2	3.307	3.307	3.307	0.023	3.309	3.312	3.311	0.027
CJ-CR3	3.488	3.482	3.485	0.011	3.490	3.492	3.491	0.017
CJ-UL1	3.003	3.005	3.004	0.017	3.010	3.009	3.010	0.023
CJ-UL2	3.517	3.519	3.518	0.012	3.523	3.524	3.524	0.018
CJ-UL3	2.855	2.850	2.853	0.027	2.854	2.856	2.855	0.029
CJ-UR1	2.928	2.928	2.928	0.011	2.936	2.933	2.935	0.018
CJ-UR2	4.002	4.003	4.003	0.022	4.002	4.004	4.003	0.023
CJ-UR3	3.526	3.526	3.526	0.007	3.525	3.528	3.527	0.008

Date/Time	11/4/2016 9:00 AM				11/9/2016 11:00 AM			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.319	3.320	3.320	0.028	3.323	3.324	3.324	0.032
CJ-SL2	3.136	3.136	3.136	0.044	3.141	3.139	3.140	0.048
CJ-SL3	3.114	3.116	3.115	0.027	3.119	3.119	3.119	0.031
CJ-SR1	2.667	2.668	2.668	0.033	2.670	2.673	2.672	0.037
CJ-SR2	2.557	2.555	2.556	0.038	2.559	2.560	2.560	0.042
CJ-SR3	3.194	3.194	3.194	0.043	3.198	3.199	3.199	0.047
CJ-CL1	3.047	3.051	3.049	0.033	3.053	3.055	3.054	0.038
CJ-CL2	3.228	3.228	3.228	0.049	3.235	3.234	3.235	0.055
CJ-CL3	2.898	2.901	2.900	0.045	2.906	2.904	2.905	0.051
CJ-CR1	3.422	3.422	3.422	0.026	3.428	3.423	3.426	0.029
CJ-CR2	3.318	3.315	3.317	0.033	3.320	3.318	3.319	0.035
CJ-CR3	3.494	3.495	3.495	0.021	3.496	3.496	3.496	0.022
CJ-UL1	3.017	3.017	3.017	0.030	3.019	3.022	3.021	0.034
CJ-UL2	3.532	3.531	3.532	0.026	3.534	3.534	3.534	0.028
CJ-UL3	2.872	2.870	2.871	0.045	2.863	2.867	2.865	0.039
CJ-UR1	2.937	2.938	2.938	0.021	2.939	2.943	2.941	0.024
CJ-UR2	4.006	4.003	4.005	0.025	4.002	4.007	4.005	0.025
CJ-UR3	3.531	3.534	3.533	0.014	3.542	3.538	3.540	0.022

Date/Time	11/16/2016 9:00 AM, 99 F		11/23/2016 10:00:00, 92 F				12/07/2016 11:00:00, 56 F			
Caliper Point	X1 (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.313	0.022	3.312	3.315	3.314	0.022	3.315	3.314	3.315	0.023
CJ-SL2	3.131	0.039	3.132	3.130	3.131	0.039	3.132	3.133	3.133	0.041
CJ-SL3	3.113	0.025	3.110	3.111	3.111	0.023	3.113	3.113	3.113	0.025
CJ-SR1	2.663	0.028	2.659	2.657	2.658	0.023	2.663	2.662	2.663	0.028
CJ-SR2	2.553	0.035	2.548	2.543	2.546	0.028	2.552	2.553	2.553	0.035
CJ-SR3	3.188	0.037	3.186	3.185	3.186	0.034	3.189	3.189	3.189	0.038
CJ-CL1	3.049	0.033	3.044	3.040	3.042	0.026	3.047	3.048	3.048	0.032
CJ-CL2	3.227	0.048	3.222	3.222	3.222	0.043	3.226	3.226	3.226	0.047
CJ-CL3	2.901	0.047	2.894	2.891	2.893	0.039	2.899	2.897	2.898	0.044
CJ-CR1	3.423	0.027	3.421	3.417	3.419	0.022	3.419	3.422	3.421	0.024
CJ-CR2	3.319	0.035	3.316	3.314	3.315	0.031	3.317	3.319	3.318	0.034
CJ-CR3	3.499	0.025	3.492	3.492	3.492	0.018	3.498	3.492	3.495	0.021
CJ-UL1	3.020	0.033	3.018	3.011	3.015	0.027	3.015	3.019	3.017	0.030
CJ-UL2	3.535	0.029	3.530	3.531	3.531	0.024	3.535	3.533	3.534	0.028
CJ-UL3	2.866	0.040	2.867	2.863	2.865	0.039	2.870	2.866	2.868	0.042
CJ-UR1	2.937	0.020	2.936	2.934	2.935	0.019	2.932	2.940	2.936	0.019
CJ-UR2	4.008	0.028	4.005	4.003	4.004	0.024	4.006	4.007	4.007	0.027
CJ-UR3	3.536	0.018	3.530	3.533	3.532	0.013	3.537	3.538	3.538	0.019

Date/Time	01/20/2017 4:00 PM, 114.5 F				02/21/2017 12:00 PM, 106.3F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.323	3.324	3.324	0.032	3.322	3.321	3.322	0.030
CJ-SL2	3.149	3.149	3.149	0.057	3.144	3.143	3.144	0.051
CJ-SL3	3.127	3.127	3.127	0.039	3.121	3.122	3.122	0.034
CJ-SR1	2.674	2.675	2.675	0.040	2.671	2.671	2.671	0.036
CJ-SR2	2.566	2.567	2.567	0.049	2.556	2.556	2.556	0.038
CJ-SR3	3.203	3.202	3.203	0.051	3.196	3.196	3.196	0.045
CJ-CL1	3.061	3.064	3.063	0.047	3.056	3.056	3.056	0.040
CJ-CL2	3.246	3.245	3.246	0.066	3.239	3.238	3.239	0.059
CJ-CL3	2.916	2.915	2.916	0.061	2.907	2.908	2.908	0.053
CJ-CR1	3.432	3.434	3.433	0.036	3.432	3.430	3.431	0.035
CJ-CR2	3.333	3.332	3.333	0.049	3.330	3.330	3.330	0.046
CJ-CR3	3.507	3.510	3.509	0.034	3.503	3.500	3.502	0.027
CJ-UL1	3.030	3.028	3.029	0.042	3.031	3.029	3.030	0.043
CJ-UL2	3.548	3.549	3.549	0.042	3.547	3.545	3.546	0.040
CJ-UL3	2.884	2.884	2.884	0.058	2.879	2.880	2.880	0.054
CJ-UR1	2.950	2.950	2.950	0.034	2.947	2.945	2.946	0.029
CJ-UR2	4.018	4.017	4.018	0.038	4.017	4.018	4.018	0.038
CJ-UR3	3.551	3.550	3.551	0.032	3.549	3.547	3.548	0.030

Date/Time	03/21/2017 11:30 AM, 75.2F				04/12/2017 4:30 PM, 91 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.326	3.327	3.327	0.035	3.326	3.326	3.326	0.035
CJ-SL2	3.146	3.148	3.147	0.055	3.147	3.146	3.147	0.054
CJ-SL3	3.125	3.126	3.126	0.037	3.126	3.126	3.126	0.038
CJ-SR1	2.677	2.677	2.677	0.043	2.676	2.676	2.676	0.042
CJ-SR2	2.567	2.565	2.566	0.048	2.562	2.564	2.563	0.045
CJ-SR3	3.203	3.202	3.203	0.051	3.200	3.200	3.200	0.049
CJ-CL1	3.063	3.062	3.063	0.047	3.062	3.061	3.062	0.045
CJ-CL2	3.245	3.245	3.245	0.066	3.243	3.243	3.243	0.064
CJ-CL3	2.915	2.916	2.916	0.061	2.913	2.912	2.913	0.058
CJ-CR1	3.432	3.433	3.433	0.036	3.431	3.433	3.432	0.035
CJ-CR2	3.332	3.332	3.332	0.048	3.332	3.332	3.332	0.048
CJ-CR3	3.507	3.505	3.506	0.032	3.504	3.502	3.503	0.029
CJ-UL1	3.031	3.030	3.031	0.043	3.030	3.030	3.030	0.043
CJ-UL2	3.547	3.547	3.547	0.041	3.547	3.547	3.547	0.041
CJ-UL3	2.879	2.880	2.880	0.054	2.873	2.875	2.874	0.048
CJ-UR1	2.947	2.948	2.948	0.031	2.946	2.946	2.946	0.030
CJ-UR2	4.020	4.021	4.021	0.041	4.019	4.019	4.019	0.039
CJ-UR3	3.550	3.550	3.550	0.031	3.550	3.550	3.550	0.031

Date/Time	05/05/2017 12:15 PM, 92.75F				05/22/2017 12:00 PM, 75.4F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.318	3.317	3.318	0.026	3.325	3.324	3.325	0.033
CJ-SL2	3.137	3.138	3.138	0.046	3.144	3.147	3.146	0.054
CJ-SL3	3.120	3.121	3.121	0.032	3.123	3.125	3.124	0.036
CJ-SR1	2.667	2.668	2.668	0.033	2.675	2.674	2.675	0.040
CJ-SR2	2.555	2.554	2.555	0.037	2.562	2.561	2.562	0.043
CJ-SR3	3.193	3.192	3.193	0.041	3.200	3.202	3.201	0.050
CJ-CL1	3.046	3.046	3.046	0.030	3.055	3.055	3.055	0.039
CJ-CL2	3.231	3.230	3.231	0.051	3.241	3.240	3.241	0.061
CJ-CL3	2.901	2.901	2.901	0.047	2.911	2.910	2.911	0.056
CJ-CR1	3.428	3.429	3.429	0.032	3.432	3.432	3.432	0.035
CJ-CR2	3.326	3.324	3.325	0.041	3.329	3.331	3.330	0.046
CJ-CR3	3.502	3.500	3.501	0.027	3.499	3.501	3.500	0.026
CJ-UL1	3.025	3.025	3.025	0.038	3.024	3.024	3.024	0.037
CJ-UL2	3.541	3.542	3.542	0.035	3.545	3.547	3.546	0.040
CJ-UL3	2.872	2.874	2.873	0.047	2.879	2.879	2.879	0.053
CJ-UR1	2.943	2.940	2.942	0.025	2.948	2.947	2.948	0.031
CJ-UR2	4.015	4.016	4.016	0.035	4.015	4.016	4.016	0.035
CJ-UR3	3.543	3.541	3.542	0.023	3.549	3.549	3.549	0.031

Date/Time	06/12/2017 4:15 PM, 96.2F				06/26/2017 10:30 AM, 85.5F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.325	3.325	3.325	0.034	3.319	3.318	3.319	0.027
CJ-SL2	3.149	3.148	3.149	0.057	3.139	3.140	3.140	0.047
CJ-SL3	3.128	3.128	3.128	0.040	3.118	3.117	3.118	0.029
CJ-SR1	2.677	2.676	2.677	0.042	2.667	2.669	2.668	0.034
CJ-SR2	2.560	2.561	2.561	0.043	2.556	2.555	2.556	0.038
CJ-SR3	3.202	3.203	3.203	0.051	3.195	3.196	3.196	0.044
CJ-CL1	3.061	3.061	3.061	0.045	3.051	3.051	3.051	0.035
CJ-CL2	3.244	3.243	3.244	0.064	3.232	3.232	3.232	0.053
CJ-CL3	2.914	2.915	2.915	0.061	2.902	2.903	2.903	0.048
CJ-CR1	3.435	3.434	3.435	0.038	3.428	3.427	3.428	0.031
CJ-CR2	3.332	3.334	3.333	0.049	3.323	3.325	3.324	0.040
CJ-CR3	3.506	3.505	3.506	0.031	3.500	3.501	3.501	0.026
CJ-UL1	3.032	3.031	3.032	0.045	3.020	3.022	3.021	0.034
CJ-UL2	3.548	3.547	3.548	0.042	3.540	3.540	3.540	0.034
CJ-UL3	2.876	2.877	2.877	0.051	2.868	2.869	2.869	0.043
CJ-UR1	2.947	2.949	2.948	0.031	2.940	2.941	2.941	0.024
CJ-UR2	4.021	4.023	4.022	0.042	4.014	4.013	4.014	0.034
CJ-UR3	3.550	3.550	3.550	0.031	3.542	3.543	3.543	0.024

Date/Time	07/10/2017 09:45 AM, 82.6F				07/24/2017 03:30 PM, 104F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.320	3.321	3.321	0.029	3.321	3.321	3.321	0.030
CJ-SL2	3.140	3.142	3.141	0.049	3.142	3.143	3.143	0.051
CJ-SL3	3.121	3.121	3.121	0.033	3.123	3.124	3.124	0.035
CJ-SR1	2.670	2.671	2.671	0.036	2.671	2.670	2.671	0.036
CJ-SR2	2.563	2.562	2.563	0.045	2.556	2.558	2.557	0.039
CJ-SR3	3.195	3.197	3.196	0.044	3.195	3.197	3.196	0.044
CJ-CL1	3.050	3.054	3.052	0.036	3.054	3.054	3.054	0.038
CJ-CL2	3.236	3.235	3.236	0.056	3.236	3.236	3.236	0.057
CJ-CL3	2.906	2.906	2.906	0.052	2.904	2.905	2.905	0.050
CJ-CR1	3.429	3.429	3.429	0.032	3.432	3.431	3.432	0.035
CJ-CR2	3.326	3.326	3.326	0.042	3.330	3.331	3.331	0.047
CJ-CR3	3.498	3.500	3.499	0.025	3.505	3.504	3.505	0.031
CJ-UL1	3.025	3.024	3.025	0.037	3.026	3.029	3.028	0.040
CJ-UL2	3.544	3.543	3.544	0.037	3.545	3.544	3.545	0.039
CJ-UL3	2.878	2.877	2.878	0.051	2.883	2.883	2.883	0.057
CJ-UR1	2.942	2.943	2.943	0.026	2.946	2.946	2.946	0.030
CJ-UR2	4.012	4.014	4.013	0.033	4.017	4.017	4.017	0.037
CJ-UR3	3.543	3.544	3.544	0.025	3.546	3.545	3.546	0.027

Date/Time	07/31/2017 04:30 PM, 118.5F				08/07/2017 04:00 PM, 85.8F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.318	3.317	3.318	0.026	3.320	3.320	3.320	0.028
CJ-SL2	3.142	3.140	3.141	0.049	3.142	3.140	3.141	0.049
CJ-SL3	3.122	3.123	3.123	0.035	3.121	3.121	3.121	0.033
CJ-SR1	2.669	2.669	2.669	0.035	2.669	2.670	2.670	0.035
CJ-SR2	2.557	2.556	2.557	0.039	2.559	2.560	2.560	0.042
CJ-SR3	3.195	3.193	3.194	0.043	3.198	3.198	3.198	0.047
CJ-CL1	3.049	3.050	3.050	0.034	3.052	3.052	3.052	0.036
CJ-CL2	3.232	3.231	3.232	0.052	3.234	3.235	3.235	0.055
CJ-CL3	2.903	2.901	2.902	0.048	2.905	2.904	2.905	0.050
CJ-CR1	3.431	3.429	3.430	0.033	3.429	3.429	3.429	0.032
CJ-CR2	3.329	3.328	3.329	0.045	3.328	3.328	3.328	0.044
CJ-CR3	3.500	3.498	3.499	0.025	3.497	3.498	3.498	0.023
CJ-UL1	3.027	3.025	3.026	0.039	3.024	3.026	3.025	0.038
CJ-UL2	3.545	3.543	3.544	0.038	3.543	3.545	3.544	0.038
CJ-UL3	2.873	2.873	2.873	0.047	2.867	2.869	2.868	0.042
CJ-UR1	2.945	2.945	2.945	0.028	2.945	2.944	2.945	0.028
CJ-UR2	4.018	4.019	4.019	0.038	4.014	4.014	4.014	0.034
CJ-UR3	3.544	3.544	3.544	0.026	3.545	3.544	3.545	0.026

Date/Time	08/21/2017 12:00 PM, 105F				09/06/2017 11:30 AM, 102.3F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.320	3.320	3.320	0.028	3.316	3.316	3.316	0.024
CJ-SL2	3.141	3.142	3.142	0.049	3.140	3.140	3.140	0.048
CJ-SL3	3.121	3.122	3.122	0.034	3.121	3.121	3.121	0.033
CJ-SR1	2.669	2.670	2.670	0.035	2.667	2.666	2.667	0.032
CJ-SR2	2.561	2.560	2.561	0.043	2.561	2.558	2.560	0.042
CJ-SR3	3.196	3.196	3.196	0.045	3.194	3.194	3.194	0.043
CJ-CL1	3.052	3.053	3.053	0.037	3.044	3.044	3.044	0.028
CJ-CL2	3.233	3.235	3.234	0.055	3.230	3.231	3.231	0.051
CJ-CL3	2.903	2.904	2.904	0.050	2.901	2.902	2.902	0.047
CJ-CR1	3.429	3.431	3.430	0.033	3.425	3.428	3.427	0.030
CJ-CR2	3.331	3.329	3.330	0.046	3.326	3.328	3.327	0.043
CJ-CR3	3.499	3.500	3.500	0.026	3.494	3.498	3.496	0.022
CJ-UL1	3.026	3.028	3.027	0.040	3.031	3.028	3.030	0.043
CJ-UL2	3.544	3.544	3.544	0.038	3.545	3.545	3.545	0.039
CJ-UL3	2.879	2.880	2.880	0.054	2.873	2.872	2.873	0.047
CJ-UR1	2.945	2.944	2.945	0.028	2.940	2.943	2.942	0.025
CJ-UR2	4.013	4.013	4.013	0.033	4.017	4.017	4.017	0.037
CJ-UR3	3.544	3.543	3.544	0.025	3.543	3.541	3.542	0.023

Date/Time	09/18/2017 11:30 AM, 108.1F				10/02/2017 09:45 AM, 78.5F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.316	3.316	3.316	0.024	3.324	3.324	3.324	0.032
CJ-SL2	3.140	3.138	3.139	0.047	3.148	3.146	3.147	0.055
CJ-SL3	3.119	3.119	3.119	0.031	3.125	3.125	3.125	0.037
CJ-SR1	2.665	2.665	2.665	0.031	2.676	2.676	2.676	0.042
CJ-SR2	2.555	2.554	2.555	0.037	2.566	2.567	2.567	0.049
CJ-SR3	3.193	3.193	3.193	0.042	3.201	3.203	3.202	0.051
CJ-CL1	3.048	3.045	3.047	0.031	3.060	3.060	3.060	0.044
CJ-CL2	3.228	3.227	3.228	0.048	3.243	3.243	3.243	0.064
CJ-CL3	2.899	2.898	2.899	0.045	2.913	2.914	2.914	0.059
CJ-CR1	3.428	3.427	3.428	0.031	3.434	3.435	3.435	0.038
CJ-CR2	3.326	3.323	3.325	0.041	3.332	3.334	3.333	0.049
CJ-CR3	3.497	3.497	3.497	0.023	3.503	3.502	3.503	0.028
CJ-UL1	3.025	3.028	3.027	0.039	3.030	3.032	3.031	0.044
CJ-UL2	3.542	3.541	3.542	0.035	3.548	3.548	3.548	0.042
CJ-UL3	2.870	2.872	2.871	0.045	2.876	2.875	2.876	0.049
CJ-UR1	2.940	2.941	2.941	0.024	2.945	2.945	2.945	0.028
CJ-UR2	4.010	4.009	4.010	0.030	4.021	4.019	4.020	0.040
CJ-UR3	3.541	3.541	3.541	0.023	3.549	3.548	3.549	0.030

Date/Time	10/16/2017 12:05 PM, 117.1F				10/30/2017 10:45 AM, 85.2F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.323	3.323	3.323	0.031	3.311	3.311	3.311	0.019
CJ-SL2	3.147	3.147	3.147	0.055	3.133	3.134	3.134	0.041
CJ-SL3	3.127	3.126	3.127	0.039	3.117	3.118	3.118	0.029
CJ-SR1	2.673	2.673	2.673	0.039	2.662	2.663	2.663	0.028
CJ-SR2	2.565	2.567	2.566	0.048	2.550	2.550	2.550	0.032
CJ-SR3	3.200	3.200	3.200	0.049	3.189	3.187	3.188	0.036
CJ-CL1	3.058	3.058	3.058	0.042	3.041	3.041	3.041	0.025
CJ-CL2	3.242	3.241	3.242	0.063	3.224	3.223	3.224	0.044
CJ-CL3	2.911	2.914	2.913	0.059	2.897	2.896	2.897	0.042
CJ-CR1	3.435	3.435	3.435	0.039	3.425	3.425	3.425	0.028
CJ-CR2	3.334	3.333	3.334	0.050	3.323	3.324	3.324	0.040
CJ-CR3	3.506	3.507	3.507	0.032	3.497	3.496	3.497	0.023
CJ-UL1	3.030	3.029	3.030	0.042	3.020	3.023	3.022	0.035
CJ-UL2	3.550	3.551	3.551	0.044	3.541	3.539	3.540	0.034
CJ-UL3	2.885	2.882	2.884	0.057	2.867	2.868	2.868	0.041
CJ-UR1	2.948	2.949	2.949	0.032	2.940	2.940	2.940	0.023
CJ-UR2	4.022	4.023	4.023	0.043	4.011	4.009	4.010	0.030
CJ-UR3	3.549	3.549	3.549	0.031	3.540	3.539	3.540	0.021

Date/Time	10/16/2017 12:05 PM, 117.1F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.323	3.323	3.323	0.031
CJ-SL2	3.147	3.147	3.147	0.055
CJ-SL3	3.127	3.126	3.127	0.039
CJ-SR1	2.673	2.673	2.673	0.039
CJ-SR2	2.565	2.567	2.566	0.048
CJ-SR3	3.200	3.200	3.200	0.049
CJ-CL1	3.058	3.058	3.058	0.042
CJ-CL2	3.242	3.241	3.242	0.063
CJ-CL3	2.911	2.914	2.913	0.059
CJ-CR1	3.435	3.435	3.435	0.039
CJ-CR2	3.334	3.333	3.334	0.050
CJ-CR3	3.506	3.507	3.507	0.032
CJ-UL1	3.030	3.029	3.030	0.042
CJ-UL2	3.550	3.551	3.551	0.044
CJ-UL3	2.885	2.882	2.884	0.057
CJ-UR1	2.948	2.949	2.949	0.032
CJ-UR2	4.022	4.023	4.023	0.043
CJ-UR3	3.549	3.549	3.549	0.031

	CJ Expansion (inches)										
Time (days)	**1**	**2**	**5**	**7**	**16**	**21**	**28**	**35**	**49**	**93**	**125**
CJ-S	0.0172	0.0330	0.0382	0.0475	0.0708	0.0788	0.0618	0.0562	0.0628	0.0892	0.0780
CJ-C	0.0228	0.0383	0.0390	0.0495	0.0687	0.0768	0.0715	0.0597	0.0672	0.0980	0.0870
CJ-U	0.0152	0.0308	0.0323	0.0393	0.0533	0.0570	0.0560	0.0488	0.0550	0.0818	0.0777
Percentage (%)											
CJ-S	0.0089	0.0172	0.0199	0.0247	0.0369	0.0411	0.0322	0.0293	0.0327	0.0464	0.0406
CJ-C	0.0119	0.0200	0.0203	0.0258	0.0358	0.0400	0.0372	0.0311	0.0350	0.0510	0.0453
CJ-U	0.0079	0.0161	0.0168	0.0205	0.0278	0.0297	0.0292	0.0254	0.0286	0.0426	0.0405

	CJ Expansion (inches)										
Time (days)	**153**	**175**	**198**	**215**	**236**	**250**	**264**	**278**	**285**	**292**	**306**
CJ-S	0.0897	0.0873	0.0715	0.0852	0.0885	0.0730	0.0787	0.0783	0.0750	0.0778	0.0778
CJ-C	0.0967	0.0935	0.0762	0.0882	0.0962	0.0780	0.0813	0.0858	0.0790	0.0807	0.0820
CJ-U	0.0803	0.0773	0.0682	0.0757	0.0805	0.0640	0.0702	0.0765	0.0722	0.0687	0.0725
Percentage (%)											
CJ-S	0.0467	0.0455	0.0372	0.0444	0.0461	0.0380	0.0410	0.0408	0.0391	0.0405	0.0405
CJ-C	0.0503	0.0487	0.0397	0.0459	0.0501	0.0406	0.0424	0.0447	0.0411	0.0420	0.0427
CJ-U	0.0418	0.0403	0.0355	0.0394	0.0419	0.0333	0.0365	0.0398	0.0376	0.0358	0.0378

	CJ Expansion (inches)			
Time (days)	**322**	**334**	**348**	**362**
CJ-S	0.0738	0.0703	0.0883	0.0867
CJ-C	0.0740	0.0727	0.0943	0.0945
CJ-U	0.0712	0.0653	0.0780	0.0832
Percentage (%)				
CJ-S	0.0385	0.0366	0.0460	0.0451
CJ-C	0.0385	0.0378	0.0491	0.0492
CJ-U	0.0371	0.0340	0.0406	0.0433

Date/Time	10/19/2016 5:15 PM			02/03/2017 9:45 AM, 47 F				02/03/2017 10:45 AM, 52 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.289	3.294	3.292	3.313	3.313	3.313	0.022	3.314	3.313	3.314	0.022
CJ-SL2	3.089	3.095	3.092	3.132	3.133	3.133	0.041	3.132	3.133	3.133	0.041
CJ-SL3	3.089	3.087	3.088	3.118	3.118	3.118	0.030	3.116	3.117	3.117	0.029
CJ-SR1	2.629	2.640	2.635	2.662	2.663	2.663	0.028	2.662	2.663	2.663	0.028
CJ-SR2	2.519	2.517	2.518	2.550	2.550	2.550	0.032	2.551	2.551	2.551	0.033
CJ-SR3	3.147	3.156	3.152	3.187	3.183	3.185	0.033	3.186	3.187	3.187	0.035
CJ-CL1	3.014	3.018	3.016	3.047	3.048	3.048	0.032	3.047	3.048	3.048	0.032
CJ-CL2	3.177	3.181	3.179	3.231	3.229	3.230	0.051	3.227	3.228	3.228	0.048
CJ-CL3	2.852	2.856	2.854	2.902	2.903	2.903	0.048	2.899	2.900	2.900	0.045
CJ-CR1	3.394	3.399	3.397	3.422	3.423	3.423	0.026	3.422	3.423	3.423	0.026
CJ-CR2	3.279	3.289	3.284	3.321	3.322	3.322	0.038	3.320	3.321	3.321	0.037
CJ-CR3	3.474	3.474	3.474	3.498	3.494	3.496	0.022	3.496	3.496	3.496	0.022
CJ-UL1	2.983	2.991	2.987	3.023	3.025	3.024	0.037	3.024	3.023	3.024	0.037
CJ-UL2	3.508	3.504	3.506	3.537	3.537	3.537	0.031	3.537	3.537	3.537	0.031
CJ-UL3	2.822	2.830	2.826	2.877	2.879	2.878	0.052	2.874	2.875	2.875	0.049
CJ-UR1	2.918	2.915	2.917	2.935	2.936	2.936	0.019	2.935	2.936	2.936	0.019
CJ-UR2	3.980	3.980	3.980	4.012	4.013	4.013	0.032	4.010	4.013	4.012	0.031
CJ-UR3	3.514	3.523	3.519	3.540	3.541	3.541	0.022	3.538	3.541	3.540	0.021

Date/Time	02/03/2017 11:45 AM, 51 F				02/03/2017 12:45 PM, 53F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.313	3.312	3.313	0.021	3.315	3.314	3.315	0.023
CJ-SL2	3.133	3.133	3.133	0.041	3.134	3.134	3.134	0.042
CJ-SL3	3.117	3.118	3.118	0.029	3.117	3.118	3.118	0.029
CJ-SR1	2.663	2.662	2.663	0.028	2.663	2.665	2.664	0.029
CJ-SR2	2.550	2.550	2.550	0.032	2.550	2.552	2.551	0.033
CJ-SR3	3.188	3.186	3.187	0.036	3.188	3.189	3.189	0.037
CJ-CL1	3.044	3.042	3.043	0.027	3.044	3.045	3.045	0.029
CJ-CL2	3.229	3.228	3.229	0.050	3.229	3.229	3.229	0.050
CJ-CL3	2.903	2.901	2.902	0.048	2.900	2.902	2.901	0.047
CJ-CR1	3.422	3.423	3.423	0.026	3.423	3.425	3.424	0.027
CJ-CR2	3.321	3.321	3.321	0.037	3.322	3.324	3.323	0.039
CJ-CR3	3.497	3.494	3.496	0.021	3.492	3.495	3.494	0.019
CJ-UL1	3.023	3.021	3.022	0.035	3.023	3.023	3.023	0.036
CJ-UL2	3.538	3.539	3.539	0.032	3.538	3.540	3.539	0.033
CJ-UL3	2.874	2.873	2.874	0.047	2.873	2.872	2.873	0.047
CJ-UR1	2.936	2.935	2.936	0.019	2.936	2.940	2.938	0.021
CJ-UR2	4.012	4.013	4.013	0.032	4.012	4.011	4.012	0.031
CJ-UR3	3.540	3.541	3.541	0.022	3.541	3.542	3.542	0.023

Date/Time	02/03/2017 01:45 PM, 53.5F				02/03/2017 02:45 PM, 52 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.313	3.313	3.313	0.022	3.313	3.312	3.313	0.021
CJ-SL2	3.133	3.134	3.134	0.041	3.134	3.134	3.134	0.042
CJ-SL3	3.117	3.118	3.118	0.029	3.116	3.117	3.117	0.029
CJ-SR1	2.663	2.664	2.664	0.029	2.664	2.663	2.664	0.029
CJ-SR2	2.550	2.551	2.551	0.033	2.550	2.551	2.551	0.033
CJ-SR3	3.187	3.189	3.188	0.036	3.188	3.189	3.189	0.037
CJ-CL1	3.045	3.044	3.045	0.029	3.044	3.045	3.045	0.029
CJ-CL2	3.229	3.229	3.229	0.050	3.228	3.229	3.229	0.050
CJ-CL3	2.901	2.901	2.901	0.047	2.899	2.900	2.900	0.045
CJ-CR1	3.424	3.425	3.425	0.028	3.423	3.423	3.423	0.027
CJ-CR2	3.322	3.323	3.323	0.039	3.322	3.322	3.322	0.038
CJ-CR3	3.491	3.494	3.493	0.019	3.494	3.494	3.494	0.020
CJ-UL1	3.021	3.022	3.022	0.034	3.019	3.021	3.020	0.033
CJ-UL2	3.539	3.540	3.540	0.034	3.539	3.540	3.540	0.034
CJ-UL3	2.875	2.873	2.874	0.048	2.873	2.873	2.873	0.047
CJ-UR1	2.935	2.933	2.934	0.018	2.936	2.936	2.936	0.019
CJ-UR2	4.012	4.013	4.013	0.032	4.011	4.011	4.011	0.031
CJ-UR3	3.539	3.543	3.541	0.023	3.542	3.541	3.542	0.023

Date/Time	02/03/2017 03:45 PM, 51F				02/03/2017 04:45 PM, 47F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.312	3.312	3.312	0.020	3.310	3.313	3.312	0.020
CJ-SL2	3.133	3.134	3.134	0.041	3.132	3.133	3.133	0.041
CJ-SL3	3.116	3.117	3.117	0.029	3.116	3.116	3.116	0.028
CJ-SR1	2.663	2.663	2.663	0.028	2.663	2.663	2.663	0.028
CJ-SR2	2.551	2.549	2.550	0.032	2.550	2.549	2.550	0.032
CJ-SR3	3.188	3.188	3.188	0.037	3.188	3.189	3.189	0.037
CJ-CL1	3.043	3.044	3.044	0.027	3.044	3.045	3.045	0.029
CJ-CL2	3.227	3.228	3.228	0.048	3.227	3.228	3.228	0.048
CJ-CL3	2.900	2.900	2.900	0.046	2.900	2.901	2.901	0.047
CJ-CR1	3.422	3.423	3.423	0.026	3.423	3.419	3.421	0.025
CJ-CR2	3.321	3.322	3.322	0.038	3.322	3.322	3.322	0.038
CJ-CR3	3.494	3.494	3.494	0.020	3.493	3.491	3.492	0.018
CJ-UL1	3.021	3.021	3.021	0.034	3.021	3.020	3.021	0.034
CJ-UL2	3.540	3.538	3.539	0.033	3.541	3.539	3.540	0.034
CJ-UL3	2.873	2.872	2.873	0.047	2.869	2.869	2.869	0.043
CJ-UR1	2.935	2.937	2.936	0.019	2.935	2.936	2.936	0.019
CJ-UR2	4.011	4.010	4.011	0.031	4.012	4.011	4.012	0.031
CJ-UR3	3.539	3.539	3.539	0.021	3.538	3.538	3.538	0.019

	CJ Expansion (inches)							
Hour	**9:45 a. m.**	**10:45 a. m.**	**11:45 a. m.**	**12:45 p. m.**	**1:45 p. m.**	**2:45 p. m.**	**3:45 p. m.**	**4:45 p. m.**
CJ-S	0.0618	0.0623	0.0623	0.0647	0.0635	0.0633	0.0625	0.0618
CJ-C	0.0722	0.0700	0.0697	0.0705	0.0702	0.0693	0.0685	0.0680
CJ-U	0.0645	0.0625	0.0628	0.0638	0.0628	0.0623	0.0613	0.0602
Percentage (%)								
CJ-S	0.0322	0.0325	0.0325	0.0337	0.0331	0.0330	0.0326	0.0322
CJ-C	0.0376	0.0365	0.0363	0.0367	0.0365	0.0361	0.0357	0.0354
CJ-U	0.0336	0.0326	0.0327	0.0332	0.0327	0.0325	0.0319	0.0313

Date/Time	10/19/2016 5:15 PM			02/10/2017 9:45 AM, 63 F				02/10/2017 10:45 AM, 64 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.289	3.294	3.292	3.312	3.313	3.313	0.021	3.313	3.313	3.313	0.022
CJ-SL2	3.089	3.095	3.092	3.131	3.134	3.133	0.040	3.134	3.134	3.134	0.042
CJ-SL3	3.089	3.087	3.088	3.112	3.114	3.113	0.025	3.115	3.115	3.115	0.027
CJ-SR1	2.629	2.640	2.635	2.661	2.661	2.661	0.027	2.663	2.662	2.663	0.028
CJ-SR2	2.519	2.517	2.518	2.553	2.551	2.552	0.034	2.551	2.554	2.553	0.035
CJ-SR3	3.147	3.156	3.152	3.189	3.187	3.188	0.036	3.189	3.188	3.189	0.037
CJ-CL1	3.014	3.018	3.016	3.045	3.045	3.045	0.029	3.045	3.045	3.045	0.029
CJ-CL2	3.177	3.181	3.179	3.224	3.224	3.224	0.045	3.225	3.225	3.225	0.046
CJ-CL3	2.852	2.856	2.854	2.900	2.901	2.901	0.047	2.902	2.900	2.901	0.047
CJ-CR1	3.394	3.399	3.397	3.422	3.422	3.422	0.026	3.424	3.424	3.424	0.027
CJ-CR2	3.279	3.289	3.284	3.322	3.322	3.322	0.038	3.323	3.322	3.323	0.039
CJ-CR3	3.474	3.474	3.474	3.501	3.502	3.502	0.027	3.496	3.499	3.498	0.023
CJ-UL1	2.983	2.991	2.987	3.021	3.024	3.023	0.035	3.023	3.025	3.024	0.037
CJ-UL2	3.508	3.504	3.506	3.540	3.540	3.540	0.034	3.538	3.539	3.539	0.032
CJ-UL3	2.822	2.830	2.826	2.866	2.869	2.868	0.042	2.868	2.869	2.869	0.043
CJ-UR1	2.918	2.915	2.917	2.939	2.938	2.939	0.022	2.935	2.938	2.937	0.020
CJ-UR2	3.980	3.980	3.980	4.013	4.014	4.014	0.034	4.014	4.013	4.014	0.034
CJ-UR3	3.514	3.523	3.519	3.540	3.539	3.540	0.021	3.538	3.540	3.539	0.020

Date/Time	02/10/2017 11:45 AM, 76 F				02/10/2017 12:45 PM, 77 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.313	3.314	3.314	0.022	3.315	3.313	3.314	0.023
CJ-SL2	3.134	3.135	3.135	0.043	3.134	3.135	3.135	0.043
CJ-SL3	3.115	3.116	3.116	0.027	3.116	3.116	3.116	0.028
CJ-SR1	2.663	2.663	2.663	0.028	2.663	2.663	2.663	0.028
CJ-SR2	2.554	2.554	2.554	0.036	2.551	2.550	2.551	0.033
CJ-SR3	3.188	3.188	3.188	0.037	3.187	3.188	3.188	0.036
CJ-CL1	3.046	3.046	3.046	0.030	3.046	3.046	3.046	0.030
CJ-CL2	3.225	3.226	3.226	0.047	3.226	3.227	3.227	0.047
CJ-CL3	2.900	2.900	2.900	0.046	2.900	2.900	2.900	0.046
CJ-CR1	3.424	3.425	3.425	0.028	3.424	3.426	3.425	0.028
CJ-CR2	3.321	3.323	3.322	0.038	3.323	3.324	3.324	0.040
CJ-CR3	3.497	3.496	3.497	0.023	3.494	3.496	3.495	0.021
CJ-UL1	3.025	3.026	3.026	0.039	3.024	3.025	3.025	0.037
CJ-UL2	3.539	3.540	3.540	0.034	3.538	3.540	3.539	0.033
CJ-UL3	2.873	2.874	2.874	0.047	2.873	2.874	2.874	0.047
CJ-UR1	2.939	2.939	2.939	0.023	2.939	2.939	2.939	0.023
CJ-UR2	4.013	4.013	4.013	0.033	4.013	4.014	4.014	0.034
CJ-UR3	3.540	3.540	3.540	0.022	3.541	3.539	3.540	0.022

Date/Time	02/10/2017 11:45 AM, 76 F				02/10/2017 12:45 PM, 77 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.313	3.314	3.314	0.022	3.315	3.313	3.314	0.023
CJ-SL2	3.134	3.135	3.135	0.043	3.134	3.135	3.135	0.043
CJ-SL3	3.115	3.116	3.116	0.027	3.116	3.116	3.116	0.028
CJ-SR1	2.663	2.663	2.663	0.028	2.663	2.663	2.663	0.028
CJ-SR2	2.554	2.554	2.554	0.036	2.551	2.550	2.551	0.033
CJ-SR3	3.188	3.188	3.188	0.037	3.187	3.188	3.188	0.036
CJ-CL1	3.046	3.046	3.046	0.030	3.046	3.046	3.046	0.030
CJ-CL2	3.225	3.226	3.226	0.047	3.226	3.227	3.227	0.047
CJ-CL3	2.900	2.900	2.900	0.046	2.900	2.900	2.900	0.046
CJ-CR1	3.424	3.425	3.425	0.028	3.424	3.426	3.425	0.028
CJ-CR2	3.321	3.323	3.322	0.038	3.323	3.324	3.324	0.040
CJ-CR3	3.497	3.496	3.497	0.023	3.494	3.496	3.495	0.021
CJ-UL1	3.025	3.026	3.026	0.039	3.024	3.025	3.025	0.037
CJ-UL2	3.539	3.540	3.540	0.034	3.538	3.540	3.539	0.033
CJ-UL3	2.873	2.874	2.874	0.047	2.873	2.874	2.874	0.047
CJ-UR1	2.939	2.939	2.939	0.023	2.939	2.939	2.939	0.023
CJ-UR2	4.013	4.013	4.013	0.033	4.013	4.014	4.014	0.034
CJ-UR3	3.540	3.540	3.540	0.022	3.541	3.539	3.540	0.022

Date/Time	02/10/2017 01:45 PM, 82.5F				02/10/2017 02:45 PM, 87 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.314	3.314	3.314	0.023	3.314	3.314	3.314	0.023
CJ-SL2	3.136	3.136	3.136	0.044	3.136	3.136	3.136	0.044
CJ-SL3	3.116	3.117	3.117	0.029	3.117	3.117	3.117	0.029
CJ-SR1	2.664	2.663	2.664	0.029	2.664	2.664	2.664	0.030
CJ-SR2	2.551	2.553	2.552	0.034	2.552	2.553	2.553	0.035
CJ-SR3	3.189	3.190	3.190	0.038	3.189	3.189	3.189	0.038
CJ-CL1	3.048	3.048	3.048	0.032	3.048	3.048	3.048	0.032
CJ-CL2	3.228	3.227	3.228	0.048	3.229	3.230	3.230	0.050
CJ-CL3	2.901	2.901	2.901	0.047	2.901	2.902	2.902	0.047
CJ-CR1	3.426	3.426	3.426	0.030	3.427	3.427	3.427	0.031
CJ-CR2	3.324	3.324	3.324	0.040	3.325	3.325	3.325	0.041
CJ-CR3	3.495	3.497	3.496	0.022	3.497	3.497	3.497	0.023
CJ-UL1	3.026	3.025	3.026	0.039	3.027	3.027	3.027	0.040
CJ-UL2	3.540	3.541	3.541	0.034	3.541	3.540	3.541	0.034
CJ-UL3	2.873	2.874	2.874	0.047	2.873	2.874	2.874	0.047
CJ-UR1	2.940	2.940	2.940	0.023	2.942	2.942	2.942	0.026
CJ-UR2	4.014	4.014	4.014	0.034	4.016	4.013	4.015	0.035
CJ-UR3	3.541	3.541	3.541	0.023	3.542	3.543	3.543	0.024

Date/Time	02/10/2017 03:45 PM, 93F				02/10/2017 04:45 PM, 89 F			
Caliper Point	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)	X1 (in.)	X2 (in.)	Avg. (in.)	dX (in.)
CJ-SL1	3.315	3.316	3.316	0.024	3.315	3.316	3.316	0.024
CJ-SL2	3.137	3.137	3.137	0.045	3.138	3.137	3.138	0.046
CJ-SL3	3.118	3.117	3.118	0.029	3.117	3.117	3.117	0.029
CJ-SR1	2.665	2.664	2.665	0.030	2.665	2.664	2.665	0.030
CJ-SR2	2.553	2.553	2.553	0.035	2.553	2.552	2.553	0.035
CJ-SR3	3.190	3.189	3.190	0.038	3.190	3.190	3.190	0.039
CJ-CL1	3.048	3.048	3.048	0.032	3.048	3.048	3.048	0.032
CJ-CL2	3.229	3.229	3.229	0.050	3.229	3.229	3.229	0.050
CJ-CL3	2.902	2.902	2.902	0.048	2.903	2.902	2.903	0.048
CJ-CR1	3.427	3.427	3.427	0.031	3.428	3.428	3.428	0.031
CJ-CR2	3.326	3.326	3.326	0.042	3.325	3.325	3.325	0.041
CJ-CR3	3.498	3.499	3.499	0.024	3.496	3.498	3.497	0.023
CJ-UL1	3.026	3.026	3.026	0.039	3.027	3.026	3.027	0.039
CJ-UL2	3.543	3.542	3.543	0.036	3.543	3.543	3.543	0.037
CJ-UL3	2.876	2.875	2.876	0.049	2.874	2.877	2.876	0.049
CJ-UR1	2.943	2.943	2.943	0.027	2.942	2.942	2.942	0.026
CJ-UR2	4.016	4.016	4.016	0.036	4.017	4.016	4.017	0.037
CJ-UR3	3.542	3.543	3.543	0.024	3.543	3.543	3.543	0.025

	CJ Expansion (inches)							
Hour	**9:45 a. m.**	**10:45 a. m.**	**11:45 a. m.**	**12:45 p. m.**	**1:45 p. m.**	**2:45 p. m.**	**3:45 p. m.**	**4:45 p. m.**
CJ-S	0.0612	0.0633	0.0643	0.0633	0.0653	0.0657	0.0672	0.0672
CJ-C	0.0705	0.0705	0.0703	0.0708	0.0730	0.0748	0.0757	0.0753
CJ-U	0.0625	0.0620	0.0655	0.0652	0.0668	0.0687	0.0705	0.0708
Percentage (%)								
CJ-S	0.0319	0.0330	0.0335	0.0330	0.0340	0.0342	0.0350	0.0350
CJ-C	0.0367	0.0367	0.0366	0.0369	0.0380	0.0390	0.0394	0.0392
CJ-U	0.0326	0.0323	0.0341	0.0339	0.0348	0.0358	0.0367	0.0369

Appendix 2 – Nail Sealability Test

Specimen Number	Pass/Fail	Post-test Observations			
		Bottom Can	Nail Shanks	Underside of Plywood	Under Sheet
DRP1009-17-A	F	none	none	feels wet to the touch	can only remove first later of WRB off of sheathing; water droplets and a darkened WRB were found between layers
DRP1009-17-B	F	none	none	feels wet to the touch	can only remove first later of WRB off of sheathing; water droplets and a darkened WRB were found between layers
DRP1009-17-C	F	none	none	feels wet to the touch	can only remove first later of WRB off of sheathing; water droplets and a darkened WRB were found between layers
DRP1009-18-A	P	none	none	none	x
DRP1009-18-B	P	none	none	none	x
DRP1009-18-C	P	none	none	none	x
DRP1009-19-A	P	none	none	none	x
DRP1009-19-B	P	none	none	none	x
DRP1009-19-C	P	none	none	none	x
DRP1009-20-A	F	1/8" of water	small water droplets on shanks	wet in almost all of the area direclty underneath the test can	x
DRP1009-20-B	P	none	none	none	x

Specimen Number	Pass/Fail	Post-test Observations			
		Bottom Can	Nail Shanks	Underside of Plywood	Under Sheet
DRP1009-20-C	F	none	none	moisture in wood around the splitting at only one of the fasteners	x
DRP1009-21-A	P	none	none	none	x
DRP1009-21-B	F	none	none	moisture in wood around the splitting at only one of the fasteners	x
DRP1009-21-C	F	1/8" of water	large water droplet on one shank	local wetness extending from each fastener in the direction of splitting	x
DRP1009-22-A	P	none	none	none	x
DRP1009-22-B	P	none	none	none	x
DRP1009-22-C	P	none	none	none	x
DRP1009-23-A	P	none	none	none	x
DRP1009-23-B	P	none	none	none	x
DRP1009-23-C	P	none	none	none	x
DRP1009-24-A	P	none	none	none	x
DRP1009-24-B	P	none	none	none	x
DRP1009-24-C	P	none	none	none	x
DRP1009-25-A	P	none	none	none	x
DRP1009-25-B	P	none	none	none	x
DRP1009-25-C	P	none	none	none	x
DRP1009-26-A	P	none	none	none	x
DRP1009-26-B	P	none	none	none	x
DRP1009-26-C	P	none	none	none	x

Specimen Number	Pass/Fail	Post-test Observations			
		Bottom Can	Nail Shanks	Underside of Plywood	Under Sheet
DRP1009-27-A	P	none	none	moisture in some area direclty underneath the test can	x
DRP1009-27-B	P	none	none	none	x
DRP1009-27-C	P	none	none	moisture in some area direclty underneath the test can	x
DRP1009-28-A	P	none	none	none	x
DRP1009-28-B	P	none	none	none	x
DRP1009-28-C	P	none	none	none	x
DRP1009-29-A	P	none	none	none	x
DRP1009-29-B	P	none	none	none	x
DRP1009-29-C	P	none	none	none	x
DRP1009-30-A	P	none	none	none	x
DRP1009-30-B	P	none	none	Some humidity observed around one of the nails.	x
DRP1009-30-C	P	none	none	none	x
DRP1009-31-A	F	1/8" of water	condensation droplets	moisture in a large area directly under the test can	x
DRP1009-31-B	F	few drops of water	condensation droplets	moisture in some area direclty underneath the test can	x
DRP1009-31-C	P	none	none	none	x

Appendix 3 – Integrated to Sheathing WRB Test

Trial #	Nail Case	Stud	Tape	5min	10min	15min	20min	30min	60min	Notes
1-1	No Nail	No	No	0.0	0.1	0.2	0.2	0.2	0.3	
1-2	No Nail	No	No	0.0	0.1	0.2	0.2	0.3	0.4	
1-3	No Nail	No	No	0.0	0.0	0.0	0.1	0.1	0.1	
2-1	No Nail + Over Tape	No	Yes	0.0	0.1	0.1	0.2	0.2	0.3	Test sheathing without fastener penetration
2-2	No Nail + Over Tape	No	Yes	0.0	0.0	0.0	0.0	0.1	0.1	Test sheathing without fastener penetration
2-3	No Nail + Over Tape	No	Yes	0.0	0.0	0.0	0.0	0.0	0.1	Test sheathing without fastener penetration
3-1	Head Flush	No	No	0.3	0.5	0.7	0.8	1.0	1.6	Drops of water falling from the shank of the nail were noticed.
3-2	Head Flush	No	No	0.1	0.2	0.2	0.2	0.3	0.5	
3-3	Head Flush	No	No	0.0	0.0	0.1	0.1	0.2	0.3	When nail is completely flush works well, but in some cases when there is some inclination of the head it behaves as Head Above case.
4-1	Head Flush	Yes	No	0.0	0.1	0.3	0.4	0.4	0.9	
4-2	Head Flush	Yes	No	0.2	0.5	0.7	0.9	1.3	2.0	Water drops were falling from in between the layers
4-3	Head Flush	Yes	No	0.0	0.0	0.0	0.1	0.1	0.2	When nail is completely flush works well, but in some cases when there is some inclination of the head more water goes into the ZIP Sheathing.
5-1	Head Deep	No	No	0.3	0.5	0.8	1.0	1.5	4.0	
5-2	Head Deep	No	No	0.1	0.2	0.3	0.4	0.6	1.5	Water drops were falling from in between the layers after 20min

Trial #	Nail Case	Stud	Tape	5min	10min	15min	20min	30min	60min	Notes
5-3	Head Deep	No	No	0.7	1.4	2.2	2.6	3.5	>5	Water almost immediately was going through the ZIP Sheathing and water drops were falling from the edges. At 60min, water was only in the bottom parto of the RILEM tube.
6-1	Overdriven	No	No	0.3	0.4	0.5	0.7	0.9	1.8	
6-2	Overdriven	No	No	2.8	4.4	>5	>5	>5	>5	Immediately water went through the ZIP Sheathing. Drops falling from around the shank perimeter.
6-3	Overdriven	No	No	>5	>5	>5	>5	>5	All Water Absorbed	Water almost immediately was going through the ZIP Sheathing. Water drops were falling from the edges and from the shank also. At 60min, there was no water in the RILEM Tube.
7-1	Head Above over Tape	No	Yes	0.1	0.2	0.3	0.4	0.5	1.0	
7-2	Head Above over Tape	No	Yes	0.2	0.3	0.4	0.5	0.5	0.9	ZIP Sheathing started absorbing water before 5min. Some damage around the shank of the nail, water went through the layers of the ZIP sheathing before falling as drops.
7-3	Head Above over Tape	No	Yes	1.2	1.9	2.5	3.0	3.5	4.3	ZIP Sheathing started absorbing water before 5min. Some damaged was done around the shank of the nail when nailing it. Water drops were falling fom that damaged area.

Trial #	Nail Case	Stud	Tape	5min	10min	15min	20min	30min	60min	Notes
8-1	Head Above Over Stretch Tape	No	Yes	0.1	0.2	0.3	0.3	0.4	0.6	
8-2	Head Above Over Stretch Tape	No	Yes	0.0	0.0	0.1	0.2	0.2	0.2	
8-3	Head Above Over Stretch Tape	No	Yes	0.0	0.0	0.0	0.1	0.1	0.2	
9-1	Overdriven	Yes	No	1.3	1.8	2.3	2.6	3.3	4.5	Before 5 min had passed, water drops were falling from the edges
9-2	Overdriven	Yes	No	0.2	0.4	0.5	0.7	1.0	1.9	Presence of water was noticed by the edges. It seems water was spreading over the area around the nail in between the layers.
9-3	Overdriven	Yes	No	>5	>5	>5	>5	>5	1/4" water from bottom	Water immediately went through the ZIP Sheathing and water drops were falling from the edges.
10-1	Head Above	No	No	2.3	3.9	4.8	>5	>5	>5	Immediately water drops were falling from the shank
10-2	Head Above	No	No	0.1	0.2	0.3	0.3	0.4	0.8	
10-3	Head Above	No	No	1.1	1.4	1.6	1.8	2.1	2.5	Water was falling from the shank before 5min had passed.

Appendix 4 – Water Repellent Test

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 1st Test	Beading Ability	Effectiveness (%) 2nd Test
1A	Silane/Siloxane	Water	N	81.73	N	89.56
1B			N	87.37	N	90.35
1C			N	87.20	N	90.44
1D			N	87.79	N	92.19
2A	Silane/Siloxane	Water	N	88.73	N	88.72
2B			N	88.91	N	89.03
2C			N	88.85	N	88.63
2D			N	88.79	N	91.89
3A	Silane	Solvent	Y	88.53	N	90.40
3B			Y	87.21	N	90.60
3C			Y	88.28	N	90.64
3D			Y	88.15	Y	92.18
4A	Siloxane	Solvent	N	92.60	N	90.17
4B			N	92.20	N	89.37
4C			N	92.59	N	89.28
4D			Y	91.37	N	91.98
5A	Potassium Methyl Siliconate	Water	Y	9.59	Y	47.35
5B			Y	5.80	Y	52.96
5C			Y	4.38	Y	16.07
5D			Y	8.71	Y	54.23
6A	Ethyl Silicate/Silane	Solvent	N	88.26	N	83.62
6B			N	88.66	N	86.55
6C			Y	90.66	N	86.51
6D			N	86.03	N	83.62

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 1st Test	Beading Ability	Effectiveness (%) 2nd Test
7A	RTV-Silicone Blend	Solvent	Y	90.91	Y	90.52
7B			Y	80.19	Y	83.21
7C			Y	89.25	Y	90.22
7D			Y	90.46	Y	92.82
8A	Silicone Emulsion	Water	Y	90.10	Y	90.23
8B			Y	88.68	Y	89.35
8C			Y	91.15	Y	90.24
8D			Y	89.17	Y	93.32
9A	RTV-Silicone Blend	Solvent	Y	93.79	Y	93.19
9B			Y	85.02	Y	88.14
9C			Y	92.28	Y	93.22
9D			Y	85.93	Y	89.11
10A	Silane/Siloxane	Water	Y	31.34	Y	64.48
10B			Y	20.93	Y	42.62
10C			Y	20.48	Y	37.43
10D			Y	19.81	Y	66.65
11A	Silane w/ Silicone Elastomer	Water	N	7.51	N	89.02
11B			N	6.20	N	89.20
11C			N	12.04	N	88.36
11D			N	11.04	N	69.92
12A	one coponent water-borne reactive sealer	Water	Y	1.73	Y	17.33
12B			Y	17.23	Y	77.79
12C			Y	19.02	Y	31.19
12D			Y	5.22	Y	57.13
13A	one component water-borne reactive sealer	Water	Y	5.70	N	5.93
13B			Y	3.82	N	3.14
13C			Y	14.00	N	3.88
13D			Y	6.20	Y	8.88

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 1st Test	Beading Ability	Effectiveness (%) 2nd Test
14A	2-component, solvent borne sealer	Solvent	Y	68.99	N	91.33
14B			Y	81.55	N	92.21
14C			Y	82.86	N	92.29
14D			Y	85.26	Y	92.56
15A	silicone rubber	Solvent	Y	3.19	Y	85.98
15B			Y	1.79	Y	86.55
15C			Y	1.72	Y	87.09
15D			Y	0.66	Y	85.01
16A	silicone rubber	Solvent	Y	1.89	Y	87.13
16B			Y	5.35	Y	87.35
16C			Y	6.08	Y	85.75
16D			Y	9.51	Y	87.97
17A	silicone rubber	Solvent	Y	54.65	Y	90.05
17B			Y	66.68	Y	90.54
17C			Y	77.35	Y	90.43
17D			Y	61.11	Y	91.81
18A	-	Water	N	-2.86	N	-3.35
18B			N	-0.85	N	-0.08
18C			N	-6.78	N	-3.79
18D			N	-2.24	Y	8.25
19A	silane/siloxane	Water	Y	76.51	N	84.28
19B			Y	70.88	N	78.46
19C			Y	51.69	N	70.23
19D			Y	61.90	Y	81.41
20A	Silane	Water	N	54.30	Y	87.49
20B			N	54.58	Y	88.19
20C			N	52.52	Y	87.15
20D			N	32.16	Y	51.65

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 1st Test	Beading Ability	Effectiveness (%) 2nd Test
21A	Silane	Solvent	Y	88.50	N	89.27
21B			Y	88.85	N	89.05
21C			Y	88.61	N	88.47
21D			N	89.69	Y	91.53
22A	Silane	Solvent	N	92.49	N	89.72
22C			N	91.93	N	91.46
22B			N	92.37	N	91.59
22D			N	93.51	Y	93.71
23A	Silane	Water	Y	89.78	Y	90.56
23B			Y	79.83	Y	92.15
23C			Y	78.72	Y	91.65
23D			Y	76.27	Y	92.90
24A	Silane	Water	Y	35.27	Y	92.83
24B			Y	35.21	Y	93.36
24C			Y	38.20	Y	93.26
24D			Y	40.48	Y	92.10
25A	silane/siloxane	Water	Y	83.75	N	84.32
25B			Y	84.45	N	86.38
25C			Y	84.21	N	86.78
25D			Y	84.03	Y	89.93
26A	silane/siloxane	Water	Y	81.46	N	86.29
26B			N	82.39	N	85.54
26C			N	82.27	N	86.41
26D			Y	82.01	Y	90.82
27A	silane/siloxane	Water	N	87.39	N	86.01
27B			N	89.72	N	86.39
27C			N	90.57	N	74.60
27D			N	91.08	Y	89.03

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 1st Test	Beading Ability	Effectiveness (%) 2nd Test
28A	silane	Water	N	72.26	N	87.10
28B			N	73.38	N	87.10
28C			N	69.34	N	87.13
28D			N	73.74	N	91.21
29A	silane	Solvent	Y	95.06	N	90.51
29B			Y	95.13	N	90.60
29C			Y	95.62	N	90.66
29D			Y	94.85	Y	93.39
30A	silane	Solvent	N	90.65	N	89.50
30B			N	90.94	N	90.22
30C			N	90.33	N	89.04
30D			N	90.93	N	91.44
31A	Thixotropic Silane-Based	Water	N	75.52	Y	88.38
31B			N	80.62	Y	88.65
31C			N	80.97	Y	88.80
31D			N	81.94	N	88.24
32A	Silane/Siloxane	Water	Y	94.06	Y	89.14
32B			Y	93.73	Y	89.31
32C			Y	93.82	Y	88.73
32D			Y	93.29	Y	89.84

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 3rd Test	Beading Ability	Effectiveness (%) 4th Test	Average (%)
1A	Silane/Siloxane	Water	N	89.09	N	88.40	87.20
1B			N	88.45	N	90.49	89.16
1C			N	89.16	N	90.52	89.33
1D			N	92.54	N	93.21	91.43
2A	Silane/Siloxane	Water	N	87.86	N	89.21	88.63
2B			N	88.50	N	89.85	89.07
2C			N	87.07	N	90.48	88.76
2D			N	93.25	N	93.92	91.96
3A	Silane	Solvent	N	89.94	N	89.27	89.53
3B			N	89.29	N	89.28	89.09
3C			N	89.83	N	90.51	89.81
3D			N	92.59	N	94.61	91.88
4A	Siloxane	Solvent	N	87.88	N	91.25	90.47
4B			N	89.92	N	91.27	90.69
4C			N	89.89	N	89.21	90.24
4D			N	92.54	N	93.17	92.26
5A	Potassium Methyl Siliconate	Water	N	52.17	P	23.20	33.07
5B			N	52.27	N	24.70	33.93
5C			N	16.96	P	16.96	13.59
5D			Y	79.95	Y	85.59	57.12
6A	Ethyl Silicate/Silane	Solvent	N	83.70	N	83.70	84.82
6B			N	86.87	N	87.49	87.39
6C			N	85.84	N	88.55	87.89
6D			N	84.31	N	87.04	85.25

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 3rd Test	Beading Ability	Effectiveness (%) 4th Test	Average (%)
7A	RTV-Silicone Blend	Solvent	P	90.98	N	92.48	91.22
7B			P	86.89	N	86.88	84.29
7C			P	91.73	N	92.48	90.92
7D			Y	91.88	P	93.91	92.26
8A	Silicone Emulsion	Water	N	87.87	N	89.90	89.53
8B			N	89.15	N	89.16	89.09
8C			N	89.10	N	91.02	90.38
8D			Y	91.10	P	94.81	92.10
9A	RTV-Silicone Blend	Solvent	P	92.60	N	93.34	93.23
9B			P	89.11	N	89.10	87.84
9C			P	94.58	N	93.90	93.50
9D			Y	89.12	P	91.84	89.00
10A	Silane/Siloxane	Water	P	63.15	N	57.34	54.08
10B			P	39.66	N	38.41	35.40
10C			P	37.47	N	37.51	33.22
10D			Y	85.52	P	91.18	65.79
11A	Silane w/ Silicone Elastomer	Water	N	87.81	N	73.58	64.48
11B			N	87.78	N	70.13	63.33
11C			N	87.42	N	57.21	61.26
11D			P	91.29	P	93.47	66.43
12A	one coponent water-borne reactive sealer	Water	Y	52.58	P	20.12	22.94
12B			Y	73.60	P	27.68	49.07
12C			Y	40.04	P	25.21	28.86
12D			Y	92.50	Y	93.75	62.15

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 3rd Test	Beading Ability	Effectiveness (%) 4th Test	Average (%)
13A	one component water-borne reactive sealer	Water	N	3.83	Y	6.95	5.60
13B			N	3.66	P	5.68	4.08
13C			N	17.52	P	6.03	10.36
13D			Y	69.20	Y	78.59	40.72
14A	2-component, solvent borne sealer	Solvent	N	91.21	N	93.72	86.31
14B			N	92.62	N	93.29	89.92
14C			N	92.64	N	93.30	90.27
14D			Y	91.96	Y	95.31	91.27
15A	silicone rubber	Solvent	P	86.39	N	85.71	65.32
15B			P	87.85	N	81.76	64.49
15C			P	86.55	N	79.83	63.80
15D			P	89.83	Y	93.23	67.18
16A	silicone rubber	Solvent	Y	87.81	Y	87.81	66.16
16B			Y	87.08	P	86.40	66.55
16C			-	-	-	-	45.92
16D			Y	90.59	Y	92.76	70.21
17A	silicone rubber	Solvent	Y	90.57	Y	90.56	81.46
17B			Y	90.63	Y	91.34	84.80
17C			Y	90.65	Y	91.37	87.45
17D			Y	93.49	Y	94.93	85.34
18A	-	Water	N	-5.76	N	28.12	4.04
18B			N	-2.70	N	27.84	6.05
18C			N	-5.84	N	30.32	3.48
18D			P	18.94	Y	25.39	12.59

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 3rd Test	Beading Ability	Effectiveness (%) 4th Test	Average (%)
19A	silane/siloxane	Water	N	87.29	N	87.30	83.84
19B			N	83.02	N	82.34	78.68
19C			N	73.04	N	63.89	64.71
19D			Y	92.23	Y	92.94	82.12
20A	Silane	Water	Y	90.87	N	92.98	81.41
20B			Y	92.23	N	92.94	81.98
20C			Y	91.53	N	92.94	81.04
20D			Y	71.68	N	81.35	59.21
21A	Silane	Solvent	N	90.13	N	91.55	89.86
21B			N	90.83	N	91.55	90.07
21C			N	90.81	N	92.23	90.03
21D			Y	92.24	N	92.24	91.42
22A	Silane	Solvent	P	90.15	N	90.86	90.81
22C			N	93.27	N	94.02	92.67
22B			-	-	-	-	91.98
22D			Y	94.02	N	94.77	94.00
23A	Silane	Water	Y	91.49	N	92.92	91.19
23B			Y	92.53	N	94.03	89.64
23C			Y	92.81	N	93.53	89.18
23D			Y	94.99	Y	93.55	89.43
24A	Silane	Water	Y	94.94	Y	96.39	79.86
24B			Y	95.68	Y	96.40	80.16
24C			Y	94.93	Y	97.11	80.88
24D			Y	96.24	Y	96.24	81.26

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 3rd Test	Beading Ability	Effectiveness (%) 4th Test	Average (%)
25A	silane/siloxane	Water	N	84.05	N	86.24	84.59
25B			N	86.41	N	88.56	86.45
25C			N	85.65	N	87.10	85.93
25D			Y	91.38	P	90.66	89.00
26A	silane/siloxane	Water	N	87.03	N	86.31	85.27
26B			N	86.35	N	87.08	85.34
26C			N	85.71	N	86.44	85.21
26D			Y	92.06	P	90.61	88.87
27A	silane/siloxane	Water	N	85.61	N	86.33	86.33
27B			N	84.82	N	87.00	86.99
27C			N	85.63	N	82.05	83.21
27D			Y	91.52	P	91.52	90.79
28A	silane	Water	Y	88.61	N	89.33	84.33
28B			Y	87.26	N	89.39	84.28
28C			Y	85.79	N	89.35	82.90
28D			Y	92.21	N	92.21	87.34
29A	silane	Solvent	N	89.39	N	90.80	91.44
29B			N	90.12	N	91.53	91.85
29C			N	90.82	N	91.52	92.16
29D			P	92.27	Y	92.97	93.37
30A	silane	Solvent	N	88.66	N	90.09	89.73
30B			N	90.09	N	91.51	90.69
30C			N	89.40	N	90.82	89.90
30D			N	91.52	N	92.22	91.53

Specimen ID	Description / Chemistry	Water Based / Solvent Based	Beading Ability	Effectiveness (%) 3rd Test	Beading Ability	Effectiveness (%) 4th Test	Average (%)
31A	Thixotropic Silane-Based	Water	N	89.79	N	91.07	86.19
31B			N	90.50	N	91.14	87.73
31C			N	89.19	N	91.10	87.52
31D			N	91.74	N	91.74	88.42
32A	Silane/Siloxane	Water	N	91.07	N	90.44	91.18
32B			N	90.41	N	91.70	91.29
32C			N	89.18	N	91.10	90.71
32D			Y	92.98	N	92.34	92.11

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