The Physics Behind Lessons Learned in a Full-Size Blindside Mock-Up

David Leslie, RWC

Polyguard Products
4101 S. Business I-45, Ennis, TX 75119
469-449-3393 • dleslie@polyguard.com

Jerry Carter Jr.

SmithGroup
500 Griswold St., Suite 1700, Detroit, MI 48226
313-442-8123 • jerry.carter@smithgroup.com

IBEC
International Institute of Building Enclosure Consultants
Formerly RCI, Inc.

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ABSTRACT

Burying a pre-applied waterproofing system between an earth retention system and newly installed concrete—never to be seen again—creates a difficult scenario whereby designers, manufacturers, and contractors are left to wonder just how well their system will perform. SmithGroup (an architectural engineering firm) partnered with a design-build contractor to develop a new university laboratory building. The building included two stories of below-grade construction and was placed at the corner of the project site close to the intersection of two streets. Based on previous success, the design-build contractor proposed the use of a specific blindside system. For the proposed system to be approved for the project, both parties agreed to perform an evaluation. A significant part of the evaluation process included the assembly and forensic deconstruction of a full-size structural shotcrete mock-up.

There are three areas of concern typically posed to all pre-applied waterproofing membranes:

- Does the system bond to the concrete?
- Will the system survive the installation of the structural shotcrete?
- Can the system resist lateral water migration?

From the lessons learned during the assembly and deconstruction of the mock-up, we will review the findings and use scientific methods with applied physics to evaluate the original assumptions and validate the findings.

SPEAKERS

DAVID LESLIE

DAVID LESLIE's experience includes product development, contracting, and consulting. His 30 years of experience have provided him with a unique insight into numerous aspects of the building enclosure. He is a published author, public speaker, expert witness, and holder of multiple patent applications. Leslie is an active member of IIBEC, a Registered Waterproofing Consultant, an ABAA Licensed Field Auditor, and a member of SWRI. It is his core belief that there is no good reason for a building to leak, and he has committed much of his career to keeping people dry.

JERRY CARTER

As a member of SmithGroup's Building Technology Studio, JERRY CARTER's primary work experience focuses on the analysis and development of exterior building enclosure systems. He specializes in the design and restoration of plazas and garden roofs, conventional roofing, and below-grade waterproofing. He also plays a key role in developing and maintaining SmithGroup's master specifications related to the exterior enclosure. Carter received his B.S. in architecture and his master of architecture from Lawrence Technological University. He has been with SmithGroup for over 11 years. He is a current vice chair for the local chapter of the Building Enclosure Council.

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INTRODUCTION

Burying a pre-applied (blindside) waterproofing system between an earth retention system and newly installed concrete—never to be seen again—creates a difficult scenario whereby designers, manufacturers, and contractors are left to wonder just how well their system will perform. The systemic issue with blindside waterproofing is that its application to concrete is never seen by the installer, hence the application name "blindside." Manufacturers of these systems typically use the term "pre-applied," which describes when the system is installed, before the concrete. The words "blindside" or "pre-applied" are synonymous and will be used throughout this paper to have the same meaning.

Figure 1 – Completed stand-alone blindside mock-up during evaluation.

The systemic issue of blindside waterproofing creates an application that is risky by nature, then begs the question, "why use it?" While it is preferable to avoid blindside waterproofing applications when possible, at times, the project specific requirements may require its inevitable use. The primary reason blindside waterproofing is used is typically the limitation to fully excavate a site. These limitations could be due to the size of the building as it relates to the lot size (zero-lot-size buildings) or obstructions to the site (adjacent roadways or buildings).

On a recent new university laboratory building, the project-specific conditions included a site that was limited in space for full excavation, which required an earth retention system and the use of blindside waterproofing to address the two stories of below-grade construction. The project team developed and performed an evaluation process that included a full-size stand-alone blindside waterproofing mock-up for a structural shotcrete wall (*Figure 1*).

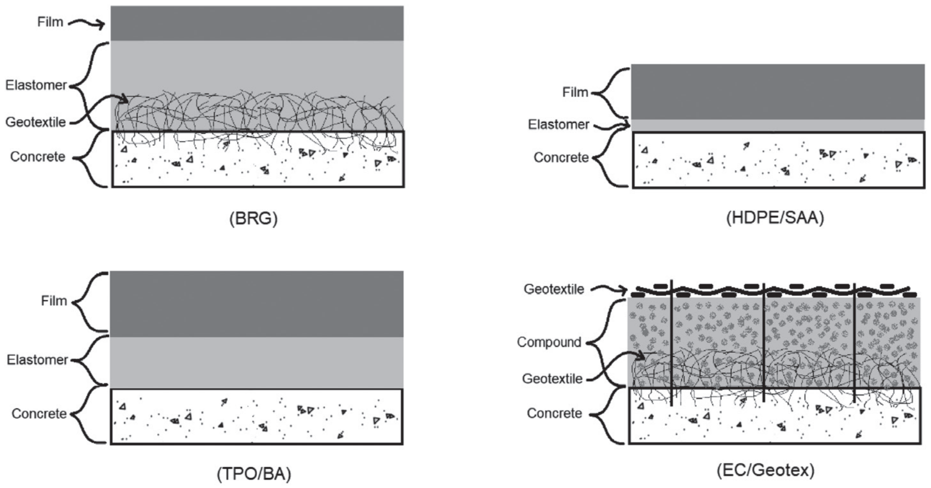
The lessons learned from the stand-alone mock-up included the following:

- Observation of the other trade's impact
- Resolving project-specific details such as:
    - — Tie-wire "striker pin" penetrations
    - — Overspray of shotcrete onto adjacent exposed waterproofing
    - — The impact of shotcrete on the membrane
    - — Detensioning of tiebacks
    - — Securement of waterproofing at end of a pour/shotcrete
- The bond of the waterproofing to the shotcrete by destructive evaluation.

These lessons learned were only possible as the mock-up was able to be viewed from the backside, which is not possible on the actual final in-situ construction. The temporary shoring wall of the mock-up was able to be deconstructed in order to observe and evaluate the waterproofing membrane. There were three surprising observations that would not have been possible without deconstructing the mock-up/shoring wall:

- The shotcrete overspray affected the bond between lifts of the concrete placement.
- Large areas of moderately consolidated shotcrete were able to be discovered.
- There was a tenacious bond of the blindside membrane to the area of well-consolidated shotcrete.

The stand-alone mock-up allowed the project team to understand the demands placed on the waterproofing system, the waterproofing installers, and the shotcrete technicians; provided insight into improving the installation processes on the project; and gave the project team a better



(BRG) (HDPE/SAA) (TPO/BA) (EC/Geotex)

Figure 2 – Illustrations of prevalent blindside waterproofing systems.

understanding of the obstacles inherent in structural shotcrete blindside waterproofing installations. For more information about the lessons learned specific to the stand-alone blindside mock-up and the process of how the evaluation of the system occurred, refer to our article that can be found in *IIBEC Interface* journal published in August 2019, titled, "Full-Scale Stand-Alone Blindside Waterproofing Mock-up and the Lessons Learned."[1]

Constructing a stand-alone full-scale mock-up not only provided the opportunity to assess the viability of the system selected for the project, but also provided the valid criteria for judgement (were we asking the right questions?). To further understand these lessons learned, one has to move beyond the observations made during the mock-up and begin asking the questions of why they are so (why does the system work?). Understanding the physics that occur during the construction of a blindside waterproofing wall may provide valuable insight for future designs of these systems. There are three benchmarks which pre-applied/blindside waterproofing systems have traditionally been measured against:

- Does the system bond to the concrete?
- Will the system survive the installation of the shotcrete?
- Can the system resist lateral water migration?

Based on these benchmarks, the following learning objectives were made:

1. Develop an understanding of a pre-applied waterproofing system within a structural shotcrete wall assembly.
2. Develop an understanding of the physics and importance of bonding a pre-applied waterproofing system to a structural shotcrete wall assembly.
3. Develop an understanding of the physics and importance for the survivability of a pre-applied waterproofing system in a structural shotcrete wall assembly.
4. Develop an understanding of the physics and importance to resist lateral water migration of a pre-applied waterproofing system in a structural shotcrete wall assembly.

An important aspect to understand is that the lessons learned and the research directed at those lessons are system-specific and were intended to assist in validating if the system was viable for this specific project. This is not to say that discoveries are not applicable to other system designs—only that the research did not test other systems at this time. The system selected and researched is composed of a backing film, rubberized asphalt, and geotextile composite membrane (BRG). Other prevalent systems that were not evaluated in this research but may find similar results include: high density polyethylene (HDPE) and shielded acrylic adhesive, thermoplastic olefin and reactive butyl alloy, and expansive compound (bentonite clay or hydrophilic polymer gel) in geotextile containment. For description purposes, the whole assembly is considered the membrane as illustrated in *Figure 2*.

LEARNING OBJECTIVE #1: Develop an understanding of a pre-applied waterproofing system within a structural shotcrete wall assembly.

A blindside wall is constructed from the outside in, beginning with an earth retention system. There are several methods of how to retain the earth. One method utilizes soldier piles and lagging that consist of steel H-piles encased in concrete with wood timber lagging boards retaining the earth. A molded sheet drainage panel was installed onto the lagging and then followed by the installation of the waterproofing membrane. The reinforcing steel for the concrete wall is then installed. In some cases, the height of the wall may dictate the need for tie-wire anchors to restrict movement of the reinforcing steel as the shotcrete is placed. It is recommended to install the tie-wire anchors prior to the reinforcing steel to allow an opportunity to detail the waterproofing around each penetration without being obstructed by reinforcing steel. The final step of the wall construction is the placement of the shotcrete (*Figure 3-1*).

In general terms, most blindside constructed walls are similar. Some designs may incorporate more items or achieve the designed components differently. For example, the design of the earth retention system is highly dependent on the conditions of the soil and the depth of the excavation. The system components previously described were used on the full-size mock-up and noted in a generic fashion. To provide a better understanding of the system, each component of the wall is described in greater detail below.

Earth Retention System

Soldier piles are placed into the soil for the appropriate depth, depending on design conditions. Some soil conditions require the piles to be stabilized with concrete. As excavation of the soil begins, the unexcavated soil is retained with wood timber lagging boards. The lagging boards are placed from the top down to the full depth of the excavation by placing each lagging board behind the inboard-facing H-pile flange. Additional lateral support will be implemented with the use of a tensioned tieback anchor.

The goal of this component is obvious: to provide additional support for the lagging wall, which ultimately retains the soil. The tiebacks can either be abandoned in place, or removed or detensioned once the foundation is completed. Some project constraints require the removal of the earth retention system, and if not accounted for, they can cause damage to a below-grade waterproofing system. However, it can be overcome in the design of the wall assembly. For the example project included in this paper, the earth retention system remained in place.

Drainage System

A molded-sheet drainage panel is often secured to the earth retention system prior to installation of the waterproofing. Many of the typical panels consist of a plastic dimple board core faced on one side with a geotextile fabric and the other side with a polyethene sheet. The fabric face is placed against the earth retention system to assist in filtering soil fines to help prevent clogging of the below-grade drainage system. This drainage layer is the first line of defense against water infiltration into the building. The drainage panel collects water and with gravity directs the water down to the footing. The water is collected into a collector box, which is similar to the molded-sheet drainage panel, but thicker, creating a higher capacity to collect the water. Due to the nature of the lagging system, a drain tile has to be installed inboard of the foundation wall rather than outboard. PVC piping is used to drain the water from the collector box through the foundation wall and into the drain tile system that sits below the basement slab. Clean-outs are typically provided inside the basement in the event of a clog in the drain tile. The drainage layer can remove a significant amount of water below grade before it reaches the waterproofing membrane.

Waterproofing Membrane

A sheet-applied membrane is commonly used for blindside waterproofing applications. The BRG system selected for the example project is a composite laminated membrane composed of 4-mil cross-laminated HDPE backer, 65 mils of rubberized asphalt, and non-woven polyester geotextile. This particular BRG system is secured through the molded-sheet drainage panel to the wood lagging of the earth retention system. Fasteners are placed at the seams and at the top of the wall assembly. Each fastener is covered by the subsequent sheet within the seam, which provides a continuous plane of membrane that does not include penetrations (*Figure 3-2*). Though penetrations should be avoided, they will occur and require detailing. Typically, the detailing will use a fluid-applied product in combination with a sheet-applied detail strip. Each sheet-applied manufacturer will vary on the required method penetrations are detailed.

The waterproofing layer is the component in the wall assembly that creates a plane where water should not pass through. ASTM D1079, Standard Terminology Relating to Roofing and Waterproofing, defines waterproofing as "treatment of a surface or structure to prevent the passage of water in its liquid phase under hydrostatic pressure." Hydrostatic pressure can be caused by ground water or perched water that is trapped above a layer of clay. For the new laboratory building, the two-story basement was above the groundwater level. Permanent groundwater is not the only source for water infiltration into a basement. Rain events are also sources for water to enter a building below grade. Though rare, utility leaks below grade could also become a source of water that infiltrates into a building. Given the use of the two-story below-grade basement—a lab space—the risk of water infiltration below grade could be detrimental to the function of the building. The waterproofing layer acts as the last line of defense to protect the below-grade portion of the building from water intrusion.

Shotcrete Wall

The final component of this assembly is the structural shotcrete wall, which includes the reinforcing steel. In lieu of a shotcrete application, cast-in-place concrete can also be used. The lab building used structural shotcrete, and the research presented in this paper was based on that application. However, similar lessons learned and learning objections could also be addressed for cast-in-place concrete.

After the placement of the concrete footing, reinforcing steel is placed in a rigid grid system. Loading requirements will affect the size of reinforcing steel, as well as the placement or spacing of the reinforcing steel. Depending on the size of the wall, some installations will require the use of tie-wire anchors to minimize the reverberations of the reinforcing steel during the placement of shotcrete.

The tie-wire anchors are installed prior to the reinforcing steel to allow the waterproofing contractor the opportunity to detail each anchor. In the case of the example project, the anchors were placed approximately in a 4- x 4-ft. grid, creating several hundred penetrations in the waterproofing membrane.

One of the successes of the stand-alone mock-up proved that this detail needs to be easily repeatable, providing a secure anchor with the appropriate depth for a fluid-applied product to be applied. By minimizing the reverberation of the reinforcing steel, the shotcrete application will have a greater success of appropriate cover around the reinforcing steel, as well as minimizing

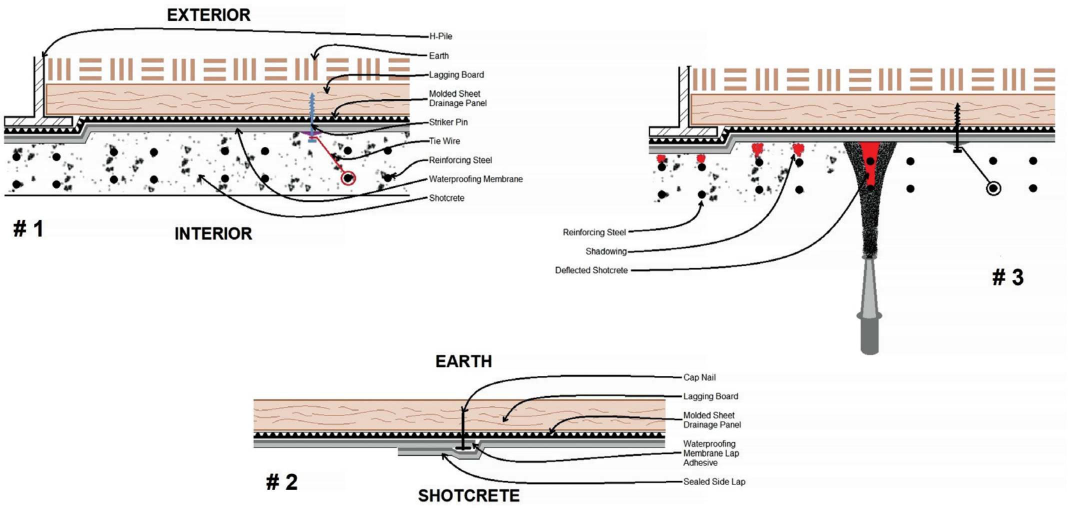


Figure 3 – 3-1: Plan detail of typical below-grade wall assembly. 3-2: Plan view of waterproofing membrane lap detail. 3-3: Illustration of shadowing in a shotcrete wall assembly.

shadowing of the shotcrete. Shadowing is the result of voids behind reinforcing steel, typically the result of a shotcrete application occurring directly perpendicular to the reinforcing steel, as well as the movement of the reinforcing steel during the shotcrete application (*Figure 3-3*).

Following the placement of reinforcing steel is the shotcrete application. Before the shooting of shotcrete begins, one last review of the waterproofing membrane is conducted, and damaged waterproofing membrane is repaired. Concrete is shot out of a nozzle at approximately 80 mph, against the waterproofing membrane. Once the depth of shotcrete is achieved, the excess material is cut away and recycled. The interior surface of the concrete is then completed with a trowel finish. Though shadowing can be detrimental to the success of the waterproofing membrane, it can also become problematic for the structural wall. The quality of shotcrete and its application by a nozzle-man can be validated with a certification process by the American Concrete Institute and the use of core samples through a stand-alone mock-up.

The completed wall assembly has multiple components, installed by different trades, with each component being relied upon for the success of the entire assembly. The system is not complete until the entire wall assembly is installed and tied into the above-grade wall. An exposed wall (or post-applied) waterproofing system is similar in that it too has multiple trades and components. However, the advantage of an exposed wall is that the waterproofed structure can be observed prior to backfill. Additionally, exposed walls do not require the numerous tie-back anchors and tie-wire striker pins that penetrate the blindside membrane. Defects or damage to a waterproofing membrane can be observed and corrected. Aside from backfill, the waterproofed structure is complete. In a blindside waterproofing application, this final observation of the waterproofing is not possible. The waterproofing installer does not apply the waterproofing to the completed structure; rather, the shotcrete (or cast-in-place concrete) is applied to the waterproofing membrane.

LEARNING OBJECTIVE #2: Develop an understanding of the physics and importance of bonding a pre-applied waterproofing system to a structural shotcrete wall assembly.

In an article published in *IIBEC Interface* by Justin Henshell and Paul Buccellato titled "Below-Grade Blindside Waterproofing Membrane Systems: A State-of-the-Art Report," the authors outline blindside waterproofing membranes into two broad categories, "Attached" and "Nonattached".[2] The selected BRG system used on the lab building is considered an attached or bonded membrane. Bonded membranes limit lateral migration of water between the membrane and the concrete substrate. The technology used to create bonded membranes is such that the manufacturers designed the system to be bonded. Data sheets for bonded membranes publish peel adhesion strength values, which describe this function for designers and demonstrate its importance in the membrane performance. As soils settle over time or the earth retention systems degrade, a bonded membrane will remain in place, whereas an unbonded membrane may fall away from the structure. The integrity of the bond of a membrane is a beneficial attribute that can contribute to the long-term performance of the structure, creating a composite that combines both attributes of each component (within the membrane and the concrete combined).

BRG systems typically achieve a bond to the concrete or shotcrete in two ways: mechanical with the geotextile, and adhesive with the internal compound. The inherent nature of blindside applications creates a scenario in which the shotcrete or concrete is applied to the waterproofing membrane. The success of the waterproofing membrane bond is directly related to the successful installation of the concrete and the capabilities of the concrete installers. Observations made during the review of the full-scale stand-alone mock-up revealed the issue of shotcrete overspray. The waterproofing membrane was well bonded to the shotcrete overspray; however, the overspray did not bond well to the next lift of shotcrete. The integrity of the waterproofing system is directly related to the integrity of the waterproofing bond. Shotcrete or concrete that is not well consolidated will not bond to the waterproofing membrane. Poor consolidation can be a result of the mix design or improper mixing of the concrete. This can create concrete that is too dry, which can become very difficult to consolidate. Shadowing—previously discussed—is also a form of poor consolidation, which can result in voids behind reinforcing steel. Poor consolidation is not the fault of the waterproofing installer, yet its impact on the successful installation is paramount.

The waterproofing membrane can become disbonded if the membrane doesn't account for shrinkage cracks that occur in concrete. For exposed waterproofing applications, the waterproofing installer has the opportunity to allow the cracks to develop

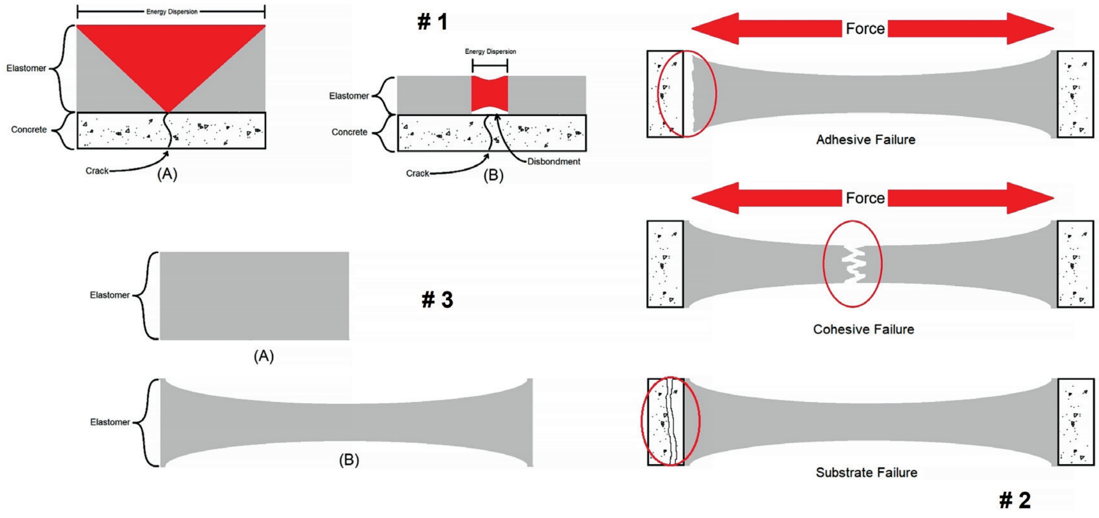


Figure 4 – 4-1: Illustration of energy dispersion through the BRG system. 4-2: Illustration of adhesive, cohesive, and substrate failure. 4-3: Illustration of elastomer change of shape during pull testing.

and provide an appropriate detail to address the cracks. Bonded blindside waterproofing membranes require the ability to bridge cracks as the concrete is applied to the waterproofing membrane. BRG systems bridge shrinkage cracks by dispersing the energy caused by the shrinkage through adequate thickness of the elastomer compound. The adequate thickness of the elastomer compound disperses the energy within the membrane at the location of the shrinkage crack. Without adequate thickness of the elastomer compound, the shrinkage crack energy will be transferred to other components within the system. *Figure 4-1* illustrates energy dispersion in the elastomeric compound: (A) energy dispersed within adequate thickness of elastomer, and (B) energy dispersed within the elastomer when disbonded from concrete.

Figure 5 – 5-1: Small mock-up pull test by hand. 5-2: Bench testing with jobsite ready-mix concrete and pull test performed with approximate 1-in. strips. 5-3: Bench testing with jobsite ready-mix concrete and adhesion of compound. 5-4: Bench testing with bag mixed concrete and poor consolidation.

When pull-testing the BRG system, the bond failure results can occur in three ways:

1. Adhesive failure in which the elastomer stays intact and debonds from the concrete.
2. Cohesive failure in which the elastomer is pulled apart and remains adhered to the concrete.
3. Substrate failure in which disbondment occurs within the concrete (*Figure 4-2*).

The compound component of the BRG system is an elastomer. When a pulling force is applied, the elastomer will stretch into an hourglass-like shape as illustrated in *Figure 4-3*. A successful test is demonstrated when a cohesive and adhesive failure of the membrane occurs. A cohesive failure of the concrete would be considered a failed test. The application of blindside waterproofing places the successful bond at the application of shotcrete, and similarly, with cast concrete.

Based on multiple bond tests, the root cause of a failed test is poor consolidation of the concrete. Consistent consolidation within shotcrete is difficult to achieve, resulting in areas of well-bonded waterproofing and areas where the concrete has cohesive failure represented by not being bonded. Regarding crack-bridging capabilities, the BRG system accounts for both bonded and disbonded areas and performs similarly as illustrated in *Figure 4-1*.

As part of the full-size stand-alone mock-up, a separate, small-scale 4- x 4-ft. mock-up was constructed. The small-scale mock-up was a backup in the event the destructive removal of the lagging boards on the backside of the full-size mock-up compromised the waterproofing bond. The small-scale mock-up provided an opportunity to verify the bond of the shotcrete to the waterproofing membrane. A cohesive failure was observed as remnants of the geotextile fabric remained in the concrete mock-up after pull testing was performed (*Figure 5-1*).

Other samples conducted as part of the research for this paper used jobsite-mixed concrete and bag-mixed concrete. The pull test for the jobsite-mixed concrete revealed remnants of the compound and geotextile on the concrete sample, demonstrating cohesive failure of the waterproofing membrane after completion of pull testing (*Figures 5-2* and *5-3*). Pull testing for the bag-mixed concrete revealed poor bonding of the membrane (*Figure 5-4*). After the membrane was removed, the revealed surface of the concrete felt sandy; that is believed to be the result of poor consolidation. Repeating the bond test for the bag-mixed concrete with considerably more water, allowing better consolidation, revealed similar results to the jobsite-mixed concrete.

Destructive evaluation of the full-scale stand-alone mock-up provided the opportunity to observe debonded areas of shotcrete. Areas of poorly consolidated shotcrete were observed on the full-scale stand-alone mock-up as a result of shotcrete overspray between lifts. The shotcrete overspray bonded successfully to the BRG system. The second lift of shotcrete revealed to be poorly consolidated around the shotcrete overspray (*Figure 6*).

Figure 6 – Full-scale stand-alone mock-up at poorly consolidated shotcrete and overspray.

Manufacturers of bonded membranes conduct ASTM D903, *Standard Test Method for Peel or Stripping Strength of Adhesive Bonds*, to failure and publish the performance value on the data sheets. The force exhibited through ASTM D903 may never occur on a membrane during its service life. However, the results represent the benchmark for a particular system to perform. The industry has not provided a recommended value for blindside membranes. However, ASTM D7832, *Standard Guide for Performance Attributes of Waterproofing Membranes Applied to Below-Grade Walls/Vertical Surfaces (Enclosing Interior Spaces)*, establishes minimum values for exposed membranes. A benchmark for minimal attributes for blindside membranes may prove to be valuable. However, for structural shotcrete applications, a guide for in-field testing methods to demonstrate successful installations may be more valuable.

LEARNING OBJECTIVE #3: Develop an understanding of the physics and importance for the survivability of a pre-applied waterproofing system in a structural shotcrete wall assembly.

As stated previously, a pre-applied system is not complete until the concrete is placed, and the pre-applied system is the substrate for the structure that is not intended to be exposed again. Considering the harsh environment that a pre-applied system is exposed to before, during, and after the placement of the concrete, being a viable waterproofing for the building is a very difficult task. When utilizing shotcrete as the concrete placement methodology, the task becomes even more challenging, considering the concrete will be shot at 80 mph at the waterproofing system. Survivability for all phases of construction is critical for producing a watertight building with a pre-applied waterproofing system.

Survivability Prior to Placement

The first phase of survivability is during the assembly of the components necessary to produce a structurally stable wall, which includes tiebacks, anchors, and rebar. After surviving the installation, the membrane needs to then survive the elements of the environment until the concrete can be placed. In the example project, the waterproofing system was applied against a wood-lagging wall that had integral wall-stabilizing tiebacks (*Figure 7-1*). Note, in this case, that some of the tiebacks were required to be detensioned after completion

Figure 7 – 7-1: Lagging wall for the stand-alone mock-up. 7-2: Molded-sheet drainage panel with integral filter fabric.

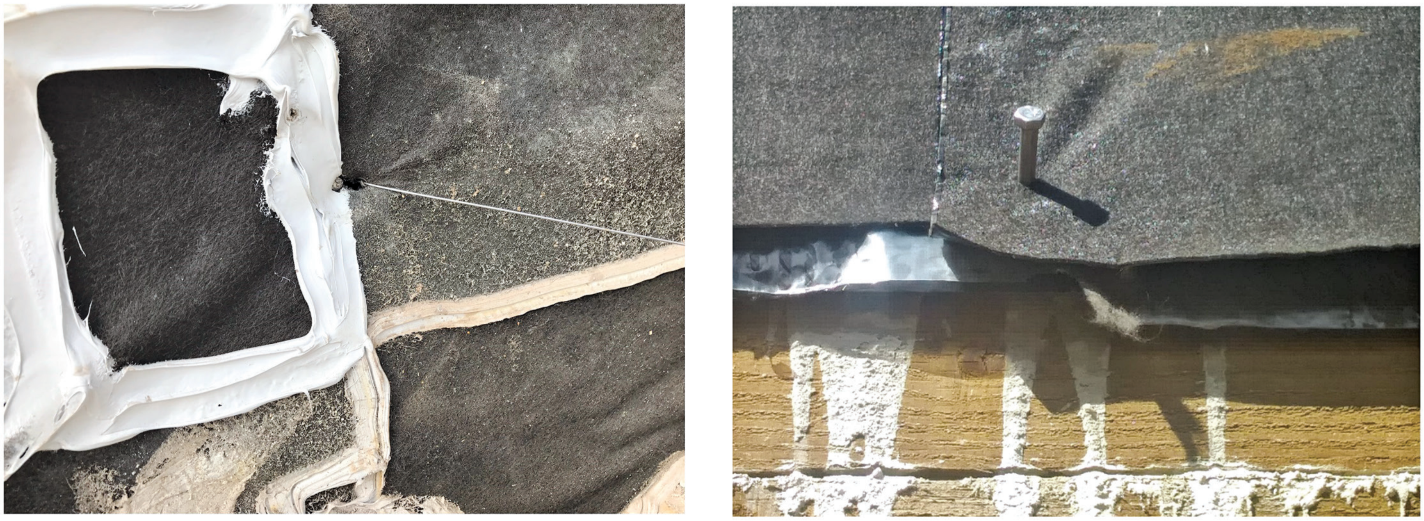


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Figure 8 – 8-1: Bent "striker pins" and damaged membrane. 8-2: Enhanced tie-wire anchor.

of the structural wall. The BRG system was installed on top of a molded-sheet drainage panel with an integral geotextile filter fabric that was applied over the lagging wall (*Figure 7-2*).

Along with providing a drain plane for rainwater runoff, the molded-sheet drainage panel provides a unitizing effect for gaps, voids, and undulations of the shoring, reducing the opportunity for puncture damage, and dispersing point loads during placement of the shotcrete.

As indicated, another important component that contributes to the structural integrity and strength of a concrete wall is the reinforcing. In shotcrete applications, the reinforcing cage must be stabilized to reduce the oscillation during placement of the shotcrete, which can create voids in the concrete. The cage is stabilized with tie-wires tied to "striker pins" (tie-wire anchors). Setting the striker pins into the shoring requires the pins to penetrate the waterproofing membrane. Sealing penetrations is a common task, but the pins typically used in non-waterproof situations posed some challenges. Initially, traditional pins were used, and then the tire-wires were installed and tightened. During the tightening of the tie-wires in the mock-up, it was observed that striker pins bent under strain and damaged the membrane (*Figure 8-1*). The resolution was to use a pin that would not bend and could be detailed with the appropriate amount of sealant (*Figure 8-2*).

The survivability prior to placement of the concrete was driven more by the lessons learned and the coordination of the trades to avoid damaging the waterproofing system than by the durability of the system. In comparison, the survivability of the waterproofing during and after the placement of concrete was directly related to the robustness of the system.

Survivability During Placement

The placement of concrete into a form lined with a pre-applied waterproofing system can be a challenging situation, but the placement of shotcrete can create a much more dynamic and challenging scenario. When evaluating the survivability of a waterproofing system, it is critical to assess the individual components and the system as a whole. The application of shotcrete applies forces that can compromise the system's watertightness by puncturing the membrane or opening the seams. After the mock-up was completed on the example project, the lagging was removed from the backside. The waterproofing was then evaluated by coring holes through the wall and by removing the waterproofing from the concrete where possible. Once we applied the lessons learned, the BRG system was found to have survived the installation of the shotcrete and functioned as intended.

The lagging wall was removed to expose the BRG system (*Figure 9*). The mock-up provided the opportunity to observe striker pins, a side lap, adhesion to well-consolidated shotcrete and poorly consolidated shotcrete via the core holes, and the overall functionality of the system. The striker pin was well sealed (green arrow). The side lap was well sealed and fully bonded (purple arrow). The consolidated shotcrete was fully bonded to the membrane and well

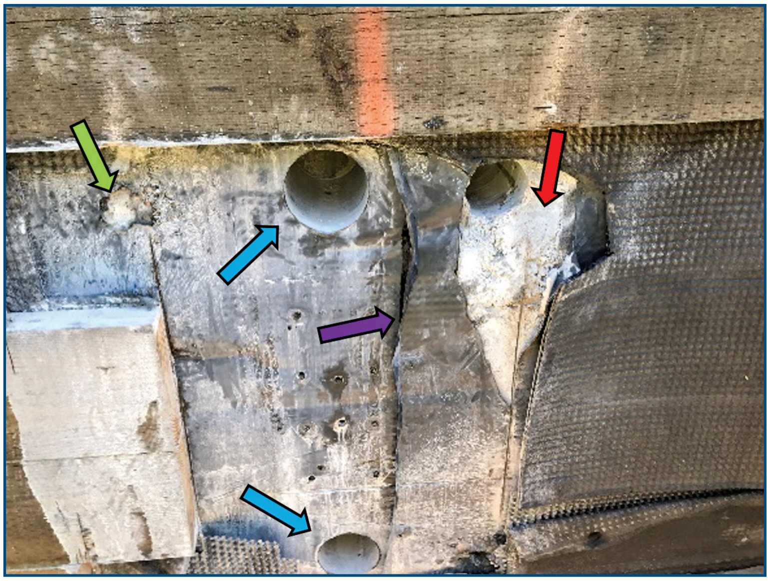


Figure 9 – Lagging removed, exposing the BRG system after deconsturcitng the installed components.

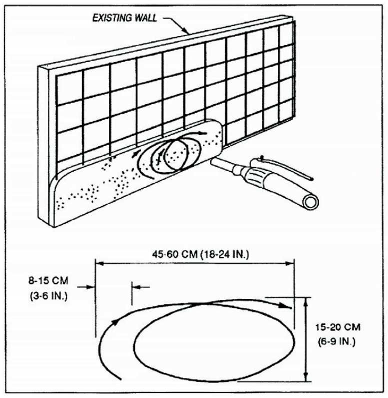
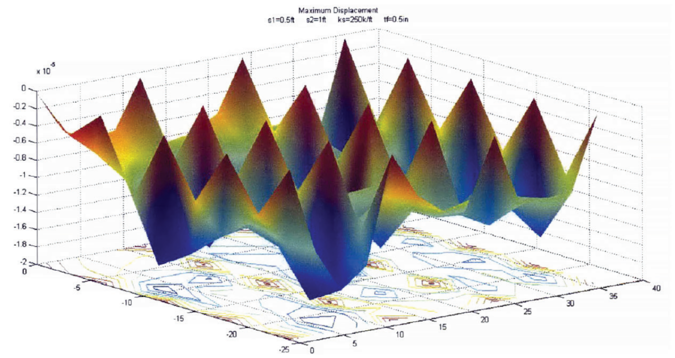


Figure 6 - Proper Nozzle Motion for Shotcrete Application

Courtesy of *Standard Practice for Shotcrete*

 # 1

8.1 Simulation A-1



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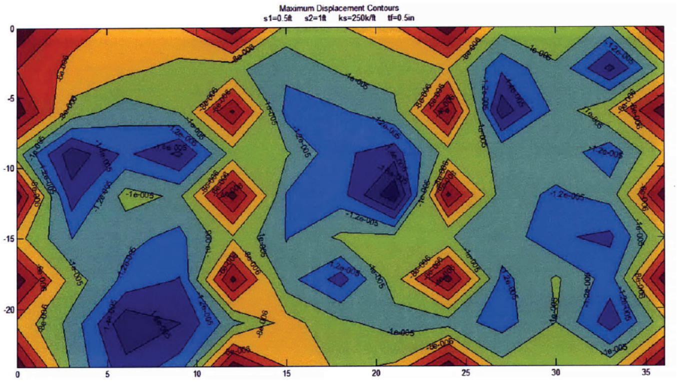

 # 4

 # 3

Figure 10 – 10-1: Illustration of shotcrete application method. 10-2: Three-dimensional color simulation indicating deflection and acceleration of formwork. 10-3: Two-dimensional color simulation indicating deflection and acceleration of formwork. 10-4: Stand-alone mock-up during shotcrete application.

integrated into the wall (blue arrows). The poorly consolidated shotcrete was partially bonded to the membrane, and substrate failure of the shotcrete was observed (red arrow).

Dynamic Forces Applied to The BRG System

To best understand the dynamic forces in applying shotcrete, a research report, "A Study of the Dynamics of Shotcrete Formwork," by Michael David,[3] can be compared to the results against the physics used in the design principles of a BRG system.

The illustration from *Standard Practices for Shotcrete*, used in "A Study of the Dynamics of Shotcrete Formworks," depicts the method used to apply shotcrete (*Figure 10-1*).[4] An important aspect to note is that the shotcrete is applied in a circular motion. During the process, the installer will have starting points and moments of lag where there will be higher concentration of impact. These focal points are areas of high abrasion and deflection of the shoring. As the waterproofing is pre-applied, the dynamic forces documented in Michael David's work are applied directly at the system causing significant stress.

The best way to grasp the concentration of force generated during the installation of shotcrete is by reviewing two and three-dimensional color simulation imaging that maps the deflection and acceleration of the formwork (*Figures 10-2* and *10-3*).These are static images from David's report depicting the concentration points illustrated in the video Simulation A-1 from Section 8.1 in his report. Simulation A-1 has two additional images that depict the rebound of the formwork. It is important to understand that each focal point not only is a point of concentrated abrasion on the membrane but is a pivot point that is applying stress on the surrounding system.

When viewing the application process of the shotcrete on the stand-alone mock-up (*Figure 10-4*), it demonstrated that the focal points were not just areas of concentrated pressure, but revealed an oscillating effect, vibrating the entire mock-up. Not only were the contact points areas of high abrasion for the membrane, but they were also an epicenter of shock that stressed other components of the assembly such as the laps and penetrations. Observing the forces that were applied to the system provided the necessary insights to understand how the waterproofing system managed forces.

As previously indicated, BRGs are typically a composite membrane (*Figure 2*). The semi-saturated geotextile provides a working surface that is trafficable (for horizontal applications) and can be handled by the installers. It can serve as a protection course to shield the membrane from impact damage and UV exposure. It also provides a mechanical bond to the concrete. The rubberized asphalt is the core waterproofing

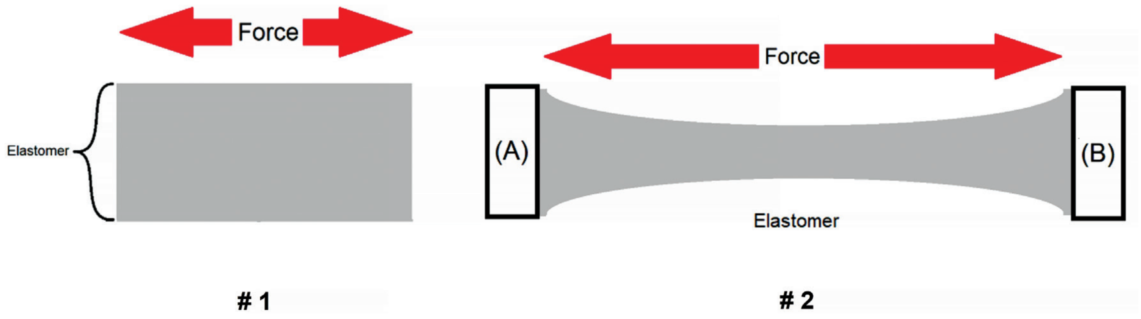

Figure 11 – 11-1: Illustration of tensile strength. 11-2: Illustration of elastic modulus.

element, provides adhesion to the concrete and laps, and disperses energy. The HDPE backing film provides abrasion resistance and adds tensile strength to the membrane. All three components together create the overall durability of the membrane.

Physics can be used to develop an understanding of why and how the BRG system performed in this specific mock-up and in general. Ultimate tensile strength, often shortened to "tensile strength," is the capacity of a material or structure to withstand loads tending to elongate (*Figure 11-1*). The benefits of tensile strength cannot be realized unless applied to match the design intent of the system. For example, if the system is designed to resist movement, high tensile strength is required, and elongation is less relevant. If the system is designed to accommodate movement, lower tensile strength is needed, and elongation becomes more important. The calculation of tensile strength for ASTM D412, *Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers—Tension*, is based on the energy exerted and the thickness of the material. The ultimate energy required to resist a load will vary relative to the thickness of the material. For example, two samples of HDPE varying in thickness and made from the same polymer will have the same tensile strength, but in application, the force required to elongate the two will differ.

Elastic modulus (also known as modulus of elasticity) is a quantity that measures an object or substance's resistance to being deformed elastically (i.e., non-permanently) when a stress is applied. Modulus is important to how energy is applied to the components attached to the elastomer. Less energy is required to elongate a low-modulus elastomer than a high-modulus elastomer. Thus, less energy is applied to other components of the assembly with a low-modulus elastomer than with a high-modulus elastomer with the same elongation and thickness (*Figure 11-2*).

BRG systems are designed to dissipate energy and accomodate movement

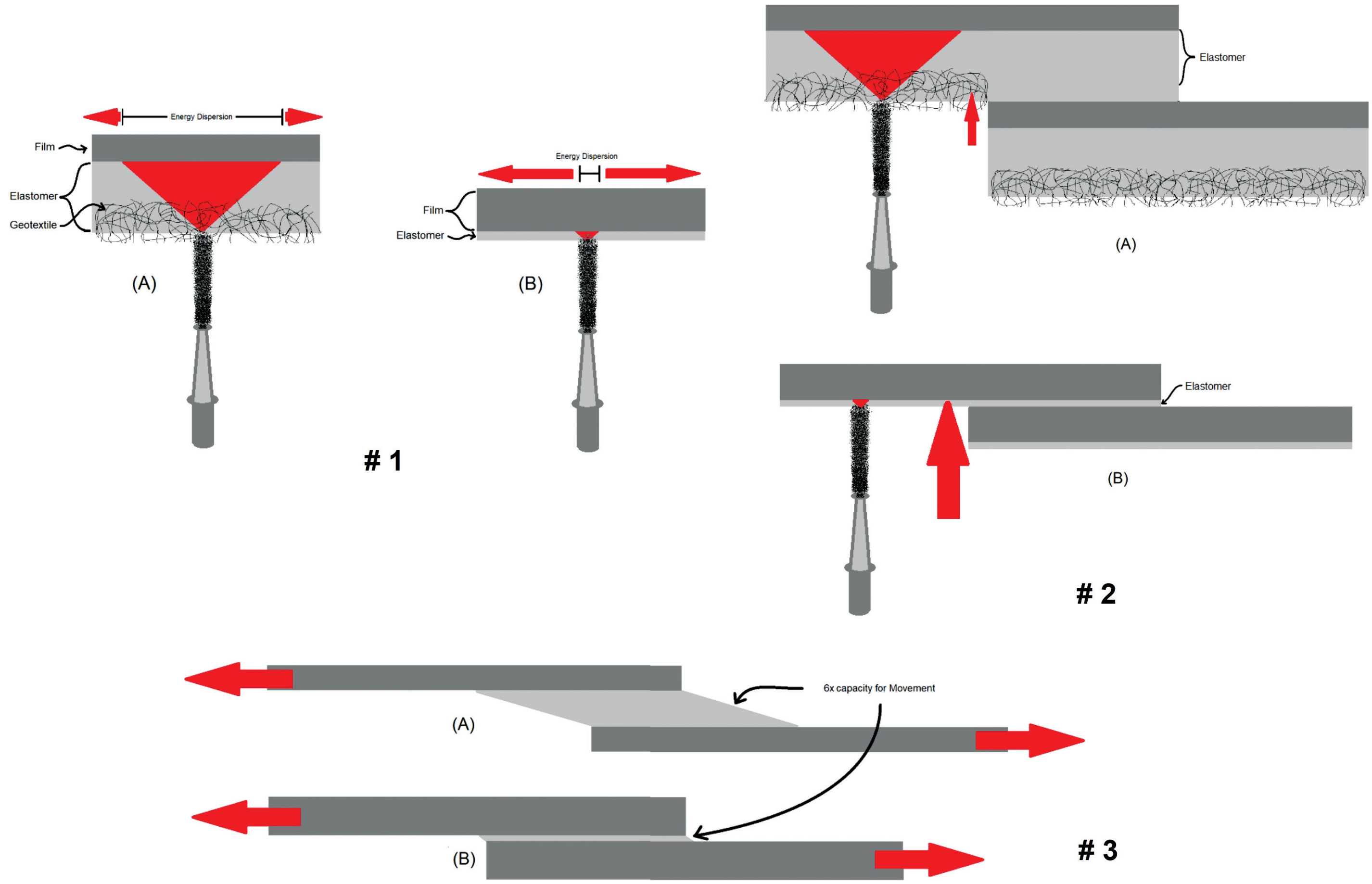

Figure 12 – 12-1-A and B: Illustrations of energy dispersion into the membrane. 12-2-A and B: Illustrations of potential energy dispersion at seams. 12-3-A and B: Illustrations of durability created by energy dispersion at seams.

compared to resisting the forces. This is a critical aspect for survivability in pre-applied waterproofing appplications, but it is even more important in the installation of shotcrete as highlighted above. As previously indicated, the non-woven geotexile is a protection course for the waterproofing element. Shotcrete is projected directly at the membrane at up to 80 mph. The geotextile absorbs the initial impact and shields the rest of the assembly from sharp edges of the aggregate. The thick layer of low-modulus elastomeric rubberized asphalt then disperses the energy that is imparted onto the HDPE backing film. BRG composite materials do well at absorbing energy and not conducting it to the rest of the system (e.g., pipe penetrations, seams, etc.). (See *Figure 12-1-A*.) In comparison, in systems that utilize a high-tensile-strength HDPE membrane with a thin layer of elastomeric adhesive, energy is distributed in the form of shock, vibration, and movement throughout the system. Though the membrane may survive, the surrounding components (e.g., pipe penetrations, seams, etc.) of the system receive much of the energy and movement, which may adversely affect the survivability of the system as a whole (*Figure 12-1-B*).

As previously discussed, the entire waterproofing system must survive the placement of concrete, and a vital part of the system is the laps. The first two key forces developed in the application of shotcrete are shock and vibration. The first blast of shotcrete generates an impact shock. The continuing application of the shotcrete creates an oscillating affect that sends vibrations out into the surrounding system. BRG systems address these forces in two ways: the membrane absorbs energy, and the low-modulus rubberized asphalt at the lap absorbs energy. As the rubberized asphalt is thick and low-modulus, less energy from the shock and vibration on the left side of the lap is imparted to the right side of the lap (*Figure 12-2-A*). For comparison, other more rigid systems distribute the vast majority of energy in the form of shock and vibration into the lap with little buffering (*Figure 12-2-B*).

The third key force developed in the application of shotcrete is caused by the movement from deflection of the shoring. Point loading from the shotcrete application can create deflection of the shoring and the pre-applied system, causing the assembly to be stretched. BRG systems address these forces in two ways: the membrane absorbs movement, and the thick, low-modulus rubberized asphalt compresses in the seams. Movement can be dispersed by the thick, low-modulus rubberized asphalt core throughout the sheet.

In addition, and similar to *Figure 10*, the compression in the seams is addressed by the thickness and modulus of the elastomer. The elastomer is able to elongate lengthwise but shrinks depthwise (*Figure 12-3-A*). More rigid systems distribute the movement directly into the lap, and there may be an insufficient amount of elastomer to accommodate the movement (*Figure 12-3-B*). Interestingly, ASTM D1876, *Standard Test Method for Peel Resistance of Adhesives* (T-Peel Test) is not a useful test to measure these effects. The installed waterproofing membrane does not receive a peel force applied at 180 degrees to the membrane surface. Two samples with the same film and compound with different thickness of compound may have similar ASTM D1876 results; however, the variance in elongation likely is not captured during the testing.

Survivability After Placement

From the research and evaluation of the full-size blindside mock-up, the BRG system was found to meet the demands of the project and demonstrated durable attributes. However, the question still remains: Will it remain watertight throughout the life of the building? Again, the concept of survivability must be based on both the membrane and the system. As described in Learning Objective #2, the system being bonded to the structure is an important attribute. Now the question becomes, how well will the components (BRG and concrete wall) function together to provide a leak-free building? Interestingly, many of the characteristics applicable to the survivability of a BRG system during placement of the shotcrete can apply to the long-term survivability and watertightness.

Infinite elongation is an attribute that contributes to how the membrane manages movement and energy at future cracks.

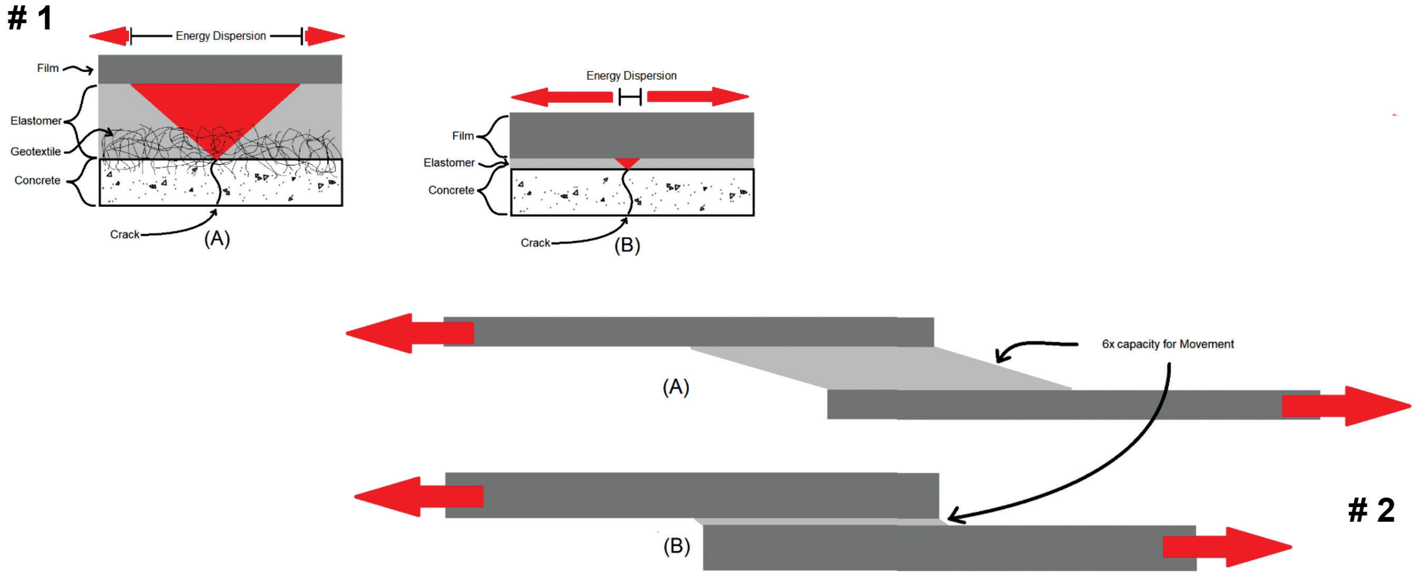

Figure 13 – 13-1-A: Illustration of energy dispersion into the system at future cracking. 13-1-B: Illustration of energy dispersion into the system at future cracking. 13-2-A: Illustration of energy dispersion into the system at lap seams. 13-2-B: Illustration of energy dispersion into the system at lap seams.

Infinite elongation is basically stretching nothing. Before a crack exists, there is infinitesimal material directly over the epicenter of the future crack. If the material directly bonded to the structure has greater adhesion to the structure than cohesion to itself, the surface material will rupture in proportion with the structure, creating a failure in the membrane. How, then, can a material pass ASTM C1305, *Standard Test Method for Crack Bridging Ability of Liquid-Applied Waterproofing Membrane*? As illustrated in *Figure 6* in Learning Objective #2, an elastomer either can address movement by having sufficient material to dissipate it or disbond from the structure to develop sufficient material to accommodate the movement. In a similar manner to how the impact of shotcrete is dissipated into a BRG membrane, the movement produced by a crack in the structure can be dissipated into the membrane (*Figure 13-1-A*). The movement from a crack into more rigid systems is directed into the rigid membrane (*Figure 13-1-B*).

Accommodation for movement at a crack within seams is similar to the method of managing movement due to the deflection of the shoring during the application of the shotcrete. The elastomer in the seams for BRG systems elongates lengthwise but shrinks depthwise. The compression in the seams is addressed by the thickness and modulus of the elastomer (*Figure 13-2-A*). More rigid membrane systems typically distribute the movement directly into the lap, and there may not be sufficient elastomer to accommodate the movement (*Figure 13-2-B*).

Deconstructing the full-size stand-alone mock-up and studying the physics relative to the BRG system design with the project construction methods provides significant insight. Comparing the observations from the mock-up with the physics of the material chosen aligns with the results. It is within reason to conclude that the BRG system should provide the long-term performance required by the project.

LEARNING OBJECTIVE #4: Develop an understanding of the physics and importance to resist lateral water migration of a pre-applied waterproofing system in a structural shotcrete wall assembly.

Over the past decade, the term "lateral water migration" (LWM) has become a driving phrase in the industry relative to pre-applied waterproofing systems. LWM is roughly understood to be the ability for water to flow along the interface of a waterproofing membrane and the adjacent substrate. As an example, we often consider the difference between a loose-laid roof membrane and a fully adhered membrane. It is often assumed that the adhered membrane would resist water migrating laterally to areas of the roof other than the point of origin better than a loose-laid membrane. Interestingly enough, it is not uncommon to find standing water within roofs with concrete decks, but there are few or no leaks inside the building. The quality of the concrete can have a significant impact on the relevance of LWM. Situations such as this example are a primary reason why there is a need to develop a clear definition, perform a deeper insight, and understand the importance of LWM in pre-applied waterproofing.

The following is a definition for LWM in pre-applied below-grade waterproofing for consideration in this paper:

> LWM: The transmission/transport of water along the interface between a bonded waterproof membrane and a water-resistant structure (one that does not allow water to pass but does allow vapor to pass) where forces are applied, which may include gravity, atmospheric, capillary, and/or head pressures

Establishing the definition is an important step for this paper as the initial bench testing results of the BRG system prior to construction of the stand-alone mock-up were sporadic and mimic the bonding observations in Learning Objective #2. Poor quality of the concrete can produce poor results of resistance to LWM. In an attempt to unify the results and potentially match the performance observed on the stand-alone mock-up, ready-mix concrete from a jobsite was used for specimens in the bench testing. Well-consolidated bench specimens were

 # 1

 # 2

 # 3

Figure 14 – 14-1: BRG membrane set in specimen form. 14-2: ¼-in. steel pipe release port. 14-3: 2-in. rupture in the membrane.

produced to create a baseline, and poorly consolidated specimens were also produced to replicate some of the issues observed at the stand-alone mock-up (*Figure 14*).

To simulate the varied ways that water impinges upon a waterproofing system, two modified ASTM test methods were used with specimens constructed from jobsite concrete: modified ASTM D5385, *Standard Test Method for Hydrostatic Pressure Resistance of Waterproofing Membranes*, and modified ASTM D5957, *Standard Guide for Flood Testing Horizontal Waterproofing Installations*. The modified ASTM D5385 test has been used previously for LWM testing of pre-applied waterproofing membranes against hydrostatic head pressure, and the modified ASTM D5857 has been used to test the effects of water not under a hydrostatic pressure.

For LWM to be properly identified, there are four key components that need to be considered that were included in the definition: "transmission/transport of water along the interface," "waterproof membrane" in conjunction with "water-resistant substrate," and "where force is being applied." These aspects should be valid for evaluating most pre-applied systems but are applied specifically to a BRG during the following testing.

Modified ASTM D5385

ASTM D5385 uses an apparatus to contain the specimen and impinge water under pressure against a membrane that is loose laid over a concrete substrate with a relief grooved scored into the block substrate. The test evaluates the membrane's resistance to hydrostatic pressure.

The modified version of the test includes casting concrete directly onto a waterproofing membrane. A pressure release port is included that touches the membrane on the interior side and passes through the concrete. A rupture is cut into the membrane on the water side. The test evaluates the ability of the assembly to resist water traveling between the membrane and the substrate from the rupture location to the port. The test specimens were cast of 3000-psi concrete onto the BRG membrane at 80°F and allowed to cure for 28 days (*Figure 14-1*). The specimens were 15.5 in. long by 8 in. wide and 6 in. deep. The pressure release port is ¼-in. steel pipe (*Figure 14-2*), and the rupture is a 1-in.-diameter hole in the membrane (*Figure 14-3*).

Traditionally, the specimen is orientated horizontally, but that method does not necessarily capture the effect of increasing head pressure on the membrane. For the tests performed for this paper, the specimen was turned vertically to allow for simulation of increasing head pressure (*Figures 15-1* to 15-4).

Specimens were produced to simulate the variable consolidation observed at the stand-alone structural shotcrete mock-up. The ports were placed with varying distances between the rupture and the pressure release port to see if there was an influence on the results.

Specimen I.D.	**LWM Results**
5385-0-C	No LWM observed
5385-2-C	LWM observed at 15 psi
5385-2-PC	LWM not applicable
5385-6-PC	LWM observed at 25 psi

To set a baseline control, a well-consolidated specimen (5385-0-C) was constructed without a pressure release port and tested for LWM. No LWM was observed, and the dyed water impinged up on the specimen and did not leave the area of the rupture (*Figure 16*).

Two specimens were constructed with the same distance between the rupture and the pressure release port. With the first specimen (*Figure 17-2*), the spacing between the rupture and the pressure release port was 2 in., and the concrete was well consolidated. For the second specimen to simulate the variable level of consolidation observed at the stand-alone structural shotcrete mock-up, the specimen (*Figure 17-4*) was constructed with the same spacing between the rupture and the pressure release port as in 5385-2-C, but the concrete was poorly consolidated.

5385-2-C (Figure 17-2)

The rupture was set at the top of the specimen, 4 in. from the three adjacent sides of the specimen, and 2 in. above the pressure release port. Water was impinged upon the speciman up to 10 psi (equivalent to 23 ft. of head pressure) for 15 minutes with no observed leakage from the pressure release port. The pressure was increased to 15 psi (equivalent to 35 feet

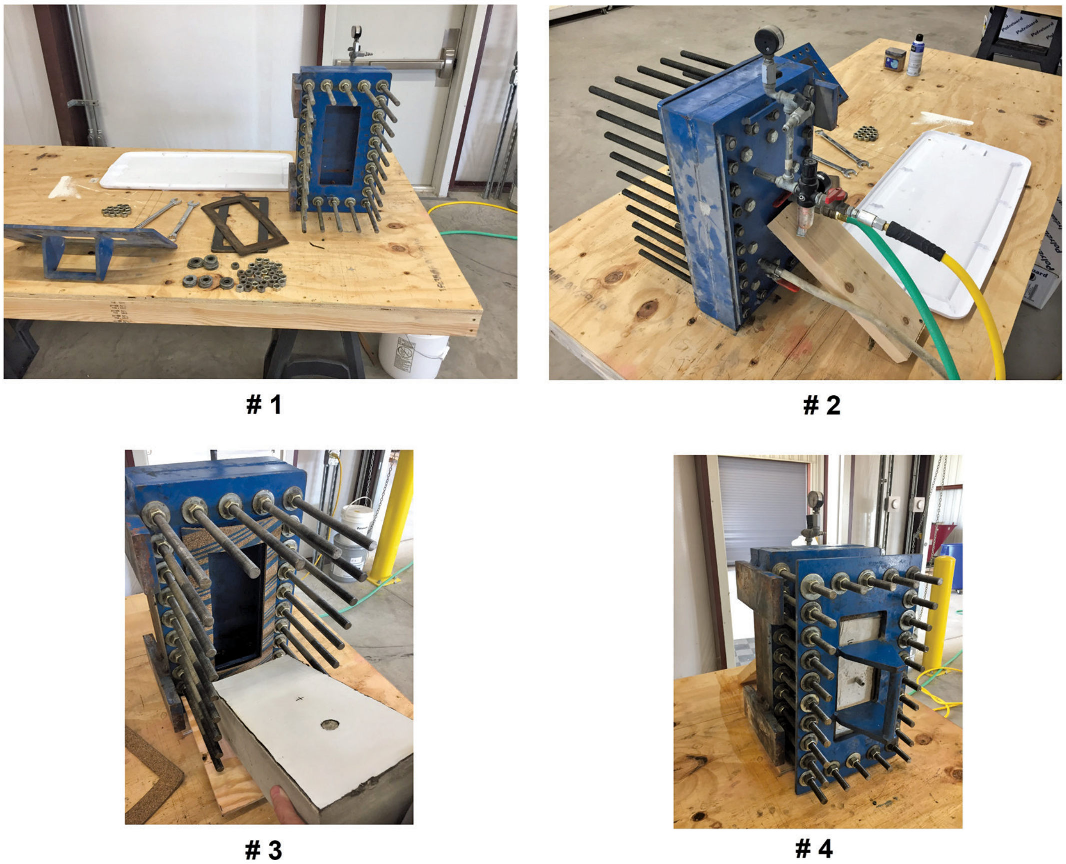
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Figure 15 – Modified D5385.

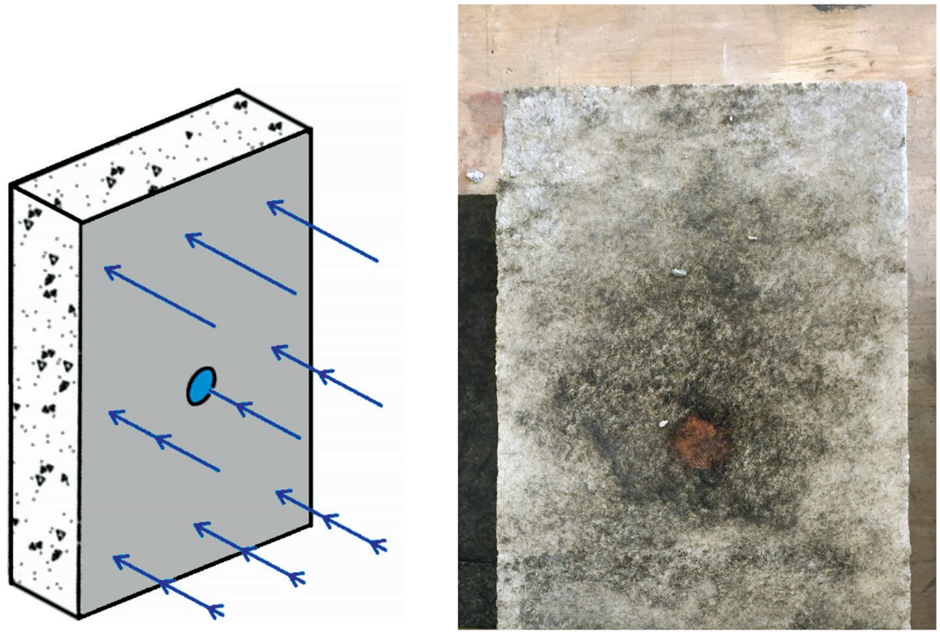

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Figure 16 – 16-1: Illustration of test specimen without a release port. 16-2: Test specimen without a release port.

of head pressure), and at approximately 3 minutes and 30 seconds into the test cycle, water was observed exiting the pressure release port. The test was stopped and the specimen was deconstructed. The path the water traveled was from the rupture to the port. The specimen did crack within the test apparatus across the port, but no water was observed exiting the crack.

5385-2-PC (Figure 17-4)

The rupture was set at the top of the specimen, 4 in. from the three adjacent sides of the specimen, and 2 in. above the pressure release port. Water was impinged upon the specimen, and water entered the specimen, then exited the port without applying pressure to the apparatus. The natural head pressure created by filling the reservoir was enough to cause water to migrate into the voids within the concrete, resulting in water migration (*Figure 17-4*). However, because the concrete is not considered water-resistant by the definition presented in this paper, the results would not be classified as LWM.

To test the effects of increased distance between the rupture and the pressure release port, combined with the variable of poorly consolidated concrete, a specimen was constructed (*Figure 18-2*).

5385-6-PC (Figure 18-2)

The rupture was set at the top of the specimen, 4 in. from the three adjacent sides of the specimen, and 6 in. above the pressure release port. Water was impinged upon the specimen up to 10 psi (equivalent to 23 ft. of head pressure) for 15 minutes with no observed leakage from the pressure release port. The pressure was increased to 15 psi (equivalent to 35 ft. of head pressure) with no water being observed exiting the pressure release port and the cycle was completed, but seepage was observed along the top of the apparatus. The pressure was increased to 20 psi (equivelant to 46 ft. of head pressure) with no water being observed exiting the pressure release port and the cycle was completed, but seepage continued to be observed along the top of the apparatus. The pressure was increased to 25 psi (equivalent to 58 ft. of head pressure) with no water being observed exiting the pressure release port and the cycle was completed, but the seepage observed along the top of the apparatus had increased. The test was stopped and the specimen was

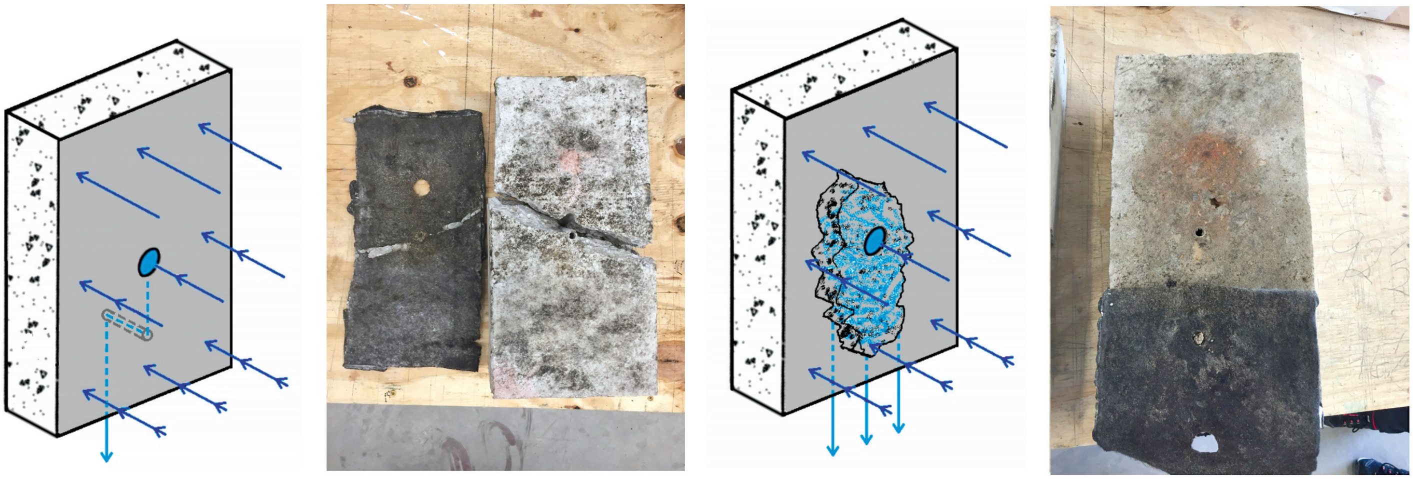

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Figure 17 – 17-1: Illustration of test specimen with a release port. 17-2: Test specimen 5385-2-c with a release port at 2 inches. 17-3: Illustration of water migration within poorly consolidated concrete. 17-4: Water migration within poorly consolidated concrete specimen 5385-2-pc.

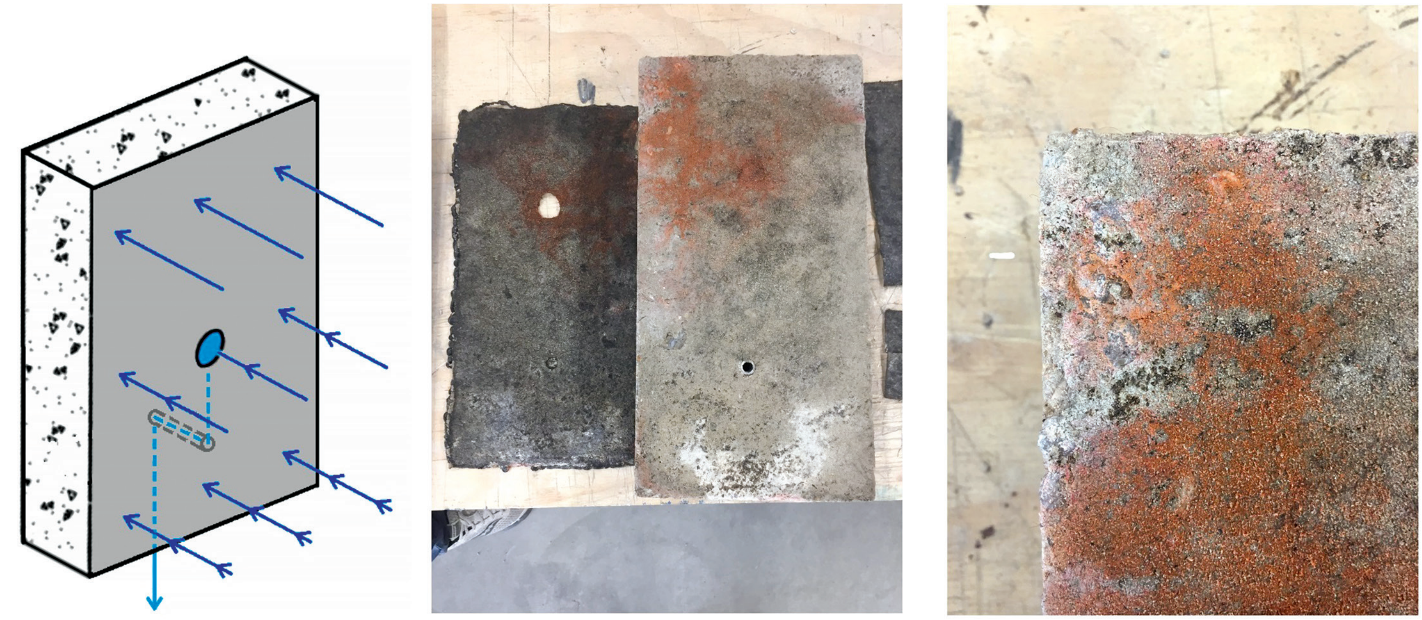
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Figure 18 – 18-1: Illustration of water migration within poorly consolidated concrete. 18-2: Test specimen with a release port at 6 inches and poorly consolidated concrete. 18-3: Close-up photo of test specimen with a release port at 6 inches and poorly consolidated concrete.

deconstructed (*Figure 18-2*). The path the water traveled was from the rupture to the area of seepage around the top of the apparatus, but it never reached the port. Under closer examination, the specimen was found to have poorly consolidated concrete in the area of seepage (*Figure 18-3*).

The specimens were based on well-consolidated concrete and produced significant insights:

1. Water did not leave the rupture area without a pressure release.
2. If a pressure release is provided and LWM is observed, the water travels to the point of the pressure release.
3. It appears that, as the distance between the rupture and the pressure port increases, greater head pressure is required to produce LWM to that port.
4. If the pressure release is removed, LWM will likely not occur.

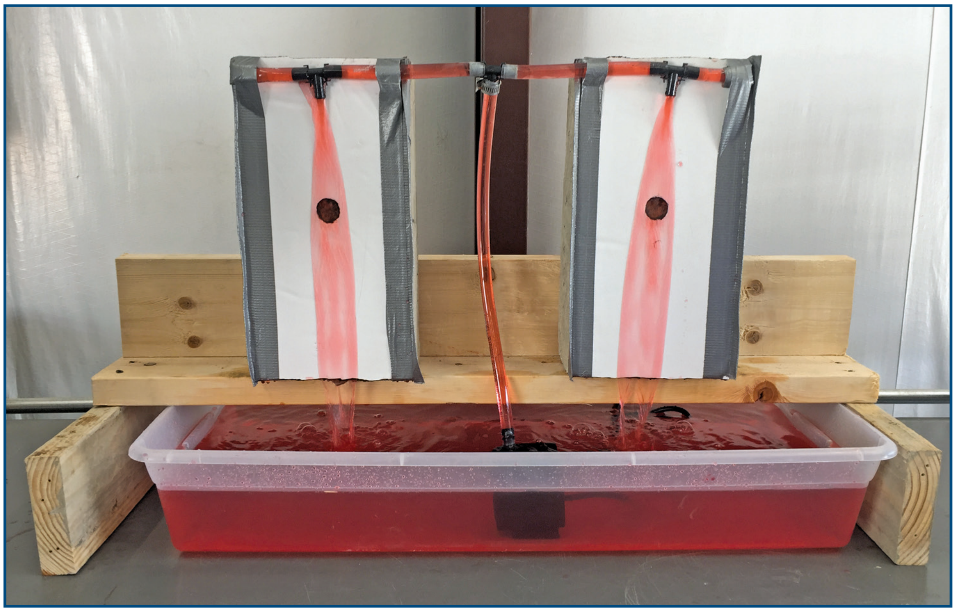
Figure 19 – Modified ASTM D5957 testing.

Unlike the well-consolidated concrete, it would be difficult to eliminate external water intrusion from entering the assembly. The multiple passageways within the simulated poorly consolidated shotcrete are the reasons for the difficulty in eliminating the water flow if a rupture were to occur. Regardless of the system, resistance to LWM (by the definintion presented in this paper) is not possible because of the natural capillary effect created with poorly consolidated concrete, and post-installation repairs are difficult to achieve.

Modified ASTM D5957

ASTM D5957 uses flooding to impinge water under moderate head pressure against a membrane to produce a visual leak. The test is intended to be used to evaluate a horizontal deck application but has been extended up onto wall flashings or sloped decks with constant water. The modified version of the test includes the same specimen types casting concrete directly onto a waterproofing membrane in the modified ASTM D5385, with the pressure release port to the interior, and having a rupture cut into the membrane on the water side. The test evaluates the ability of the assembly to resist water traveling between the membrane and the concrete from the

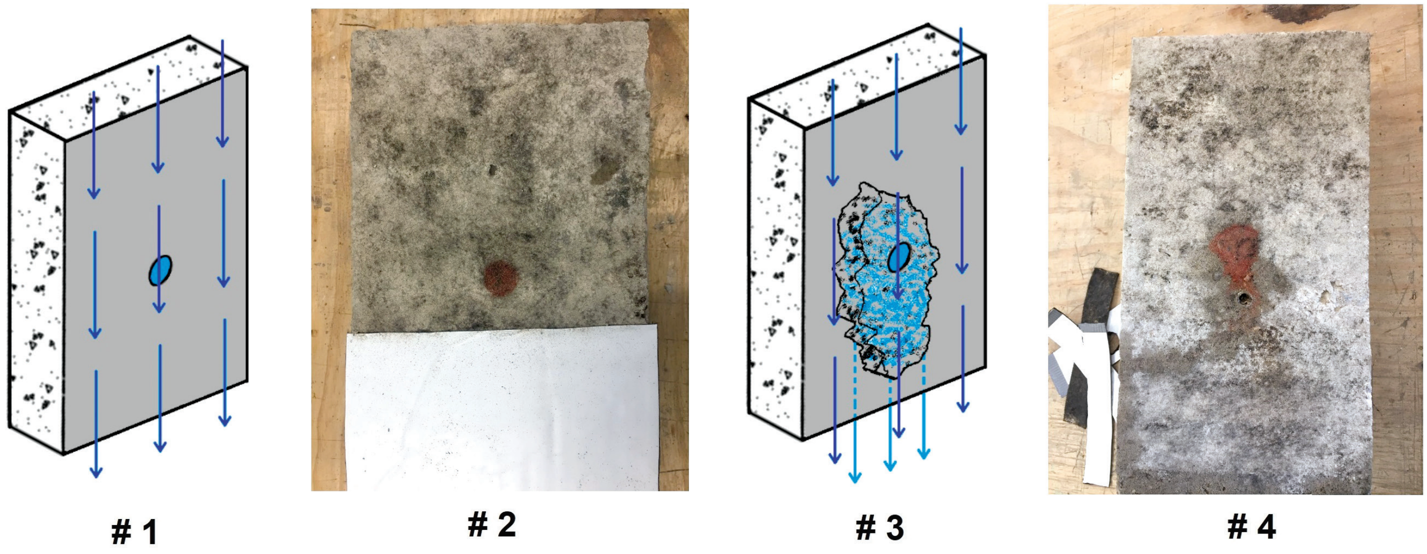

Figure 20 – 20-1: Illustration of modified ASTM D5957. 20-2: Modified ASTM D5957 with no LWM. 20-3: Illustration of modified ASTM D5957 of poorly consolidated concrete with no LWM. 20-4: Water migration of poorly consolidated concrete with no LWM.

rupture to the port under water flow without head pressure (*Figure 19*). The test was run continuously for 24 hours.

Specimens were produced to simulate the varied concrete consolidation observed at the stand-alone structural shotcrete mock-up (*Figure 20*). The test and specimen simulate the typical application of a pre-applied waterproofing system that is not in a water table nor in a hydrostatic pressure situation.

Specimen I.D.	**LWM Results**
5957-0-C	No LWM observed
5957-0-PC	LWM not applicable

To set a baseline, the test was performed on well-consolidated specimens without a port (5957-0-C). The specimen was found not to have water exiting the area of the rupture, and no LWM was observed. (*Figure 20-2*).

5957-0-PC (Figure 20-4)

With the simple application of flowing water, water entered the specimen 5957-0-PC (*Figure 20-4*) and exited the port. The surface tension of the water and porosity of the poorly consolidated concrete were sufficient to cause water to migrate into the voids within the concrete, resulting in LWM (*Figure 20-4*). Since the concrete is not considered water-resistant, the results would not be classified as LWM.

Unlike the well-consolidated concrete, it will be difficult to eliminate external water intrusion from entering the assembly. The multiple passageways within the simulated shotcrete are the reasons for the difficulty in eliminating the water flow if a rupture were to occur (*Figure 20-4*). The concrete has a natural capillary effect and numerous venting ports. Regardless of the system, resistance to LWM is not possible and post-installation repairs are difficult to achieve.

Based on the research and limited testing performed, it became apparent that in a shotcrete application, a common false positive of LWM is related to the concrete structure. Though water may migrate within the assembly, often it is not traveling between the contact point of the waterproofing and the structure. The water could potentially be transferring within the concrete itself, causing the false positive, as the structure is not water-resistant. In this case, the water migrating within the assembly is not considered LWM per the proposed definition. LWM is a desirable attribute of attached waterproofing membranes because it isolates water in the area of a rupture; however, because of the nature of shotcrete, LWM is limited to resisting water migration within the shotcrete wall. The actual occurrence of LWM within the BRG system for shotcrete applications is limited to isolated situations where there is a rupture in the system, well-consolidated concrete, and elevated hydrostatic pressure.

Considering the observed survivability of BRG systems, the design of the system accommodates the physics of the shotcrete application and is no more difficult to correct. When evaluating any pre-applied waterproofing system's in-service performance, the evaluation should consider all of the physics involved and not solely rely on one attribute. A battery of tests needs to be developed that considers all of the factors required to produce repeatable long-term success with a pre-applied waterproofing system.

CONCLUSION

Full-scale blindside mock-ups have proved to be valuable, as most mock-ups do. Every building is unique with different variables that are learned on a project. A mock-up provides an opportunity to set the stage and establish the standard for quality for all stakeholders involved. The lessons learned from the deconstruction process of the mock-up provided the platform for discussing the physics behind a blindside structural shotcrete wall. The in-depth research presented in this paper is not intended to resolve every issue for every system that is available. However, general conclusions can be made that may be applicable to many structural shotcrete basement walls, in that one could develop criteria to evaluate whether a system is viable for their project-specific conditions.

This study began with three benchmarks for blindside waterproofing applications and addressed four learning objectives. The first learning objective demonstrated how a blindside wall is constructed from the outside in, with the last component—shotcrete—applied to the waterproofing system. The second learning objective outlined critical flaws in a structural shotcrete wall, providing insight into its importance of proper consolidation to achieve a quality bond to the BRG waterproofing system. The third learning objective described and evaluated the significant forces that a shotcrete application has on a blindside waterproofing membrane. The final learning objective evaluated the issues related to lateral water migration by considering the concrete substrate's inability to resist water intrusion if poorly executed.

Based on a combination of research and the lessons learned from the standalone mock-up, the backing film, rubberized asphalt, geotextile composite membrane system appeared to be a viable waterproofing solution for the project. It is generally understood that the waterproofing membranes should bond to the concrete or shotcrete substrate. Shotcrete applications have a greater impact on the system's success than any other components in the system or than cast concrete.

As an industry, a shift in our design process should begin to evaluate blindside waterproofing systems by analyzing how the shotcrete is applied to the waterproofing membrane. The evaluation begins with the understanding that the pre-applied waterproofing membrane is the substrate that receives the concrete. The waterproofing system is not complete until the concrete is applied, and it is an important component for the overall system to function at its maximum performance. The goal to create a watertight system begins with a watertight substrate, the waterproofing membrane. The system is complete after the concrete is applied, creating a composite system with the goal that it remains watertight at the completion of the concrete application.

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