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Flood Resilience of Traditional Building Materials

Report of simulated flood immersion according to ASTM E3075 standard procedures

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Final report

Prepared for National Park Service
Washington, DC 20240

Under Project 473944, “Resilience Of Traditional Materials”

Abstract

Following the directives of the Secretary of the Interior's Standards for the Treatment of Historic Properties and the FY18-22 United States Army Corps of Engineers Campaign Plan, the National Park Service Technical Preservation Services and the United States Army Construction Engineering Research Laboratory collaborated on a project titled, "Resilience of Traditional Materials." The team sourced materials for, constructed, and tested five brick wall assemblies, seven wood frame wall assemblies, and four floor assemblies in simulated flood conditions according to standard procedures set forth in ASTM E3075-16, "Standard Test Method for Water Immersion and Drying for Evaluation of Flood Damage Resistance." The results helped the team to classify historical building materials in the context of Federal Emergency Management Agency guidelines for flood resistance. In general, most materials performed as expected, but further work is required in order to fully characterize individual materials and different types of flood conditions.

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Preface

This study was conducted for The National Park Service (NPS) under Project 473944, "Resilience of Traditional Materials." The technical monitor was Dr. Peter B. Stynoski, CEERD-CFM.

The work was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Ms. Vicki L. Vanblaricum was Chief, CEERD-CFM; Mr. Donald K. Hicks was Chief, CEERD-CF; and Mr. Alan Anderson, CEERD-CZT was the Technical Director for Environmental Quality and Installations. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti and the Director was Dr. Lance D. Hansen.

The Commander of ERDC was COL Ivan P. Beckman and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
ounces (U.S. fluid)	2.957353 E-05	cubic meters
pints (U.S. liquid)	4.73176 E-04	cubic meters
pints (U.S. liquid)	0.473176	liters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
quarts (U.S. liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

1 Introduction

1.1 Background

In accordance with the Secretary of the Interior's Standards for the Treatment of Historic Properties, the National Park Service (NPS) is developing a new Preservation Brief publication (https://www.nps.gov/tps/how-to-preserve/briefs.htm) to address the preservation and rehabilitation of historic structures in regions prone to flooding. In addition, the FY18-22 United States Army Corps of Engineers (USACE) Campaign Plan identifies, "Goal 3 – Reduce Disaster Risk," as a major initiative, with key Objectives 3b, "Enhance interagency disaster recovery capabilities," and 3c, "Enhance interagency disaster mitigation capabilities." More specifically, the shared interest of the NPS and the USACE in this endeavor stems from Action 3c2, "Enhance capacity to reduce the Nation's Flood Risk."

This report describes a set of tests performed by the USACE Engineer Research and Development Center Construction Engineering Research Laboratory (ERDC-CERL) in accordance with ASTM E3075-16, "Standard Test Method for Water Immersion and Drying for Evaluation of Flood Damage Resistance." Little scientific research has occurred in the United States of America (USA) to determine the behavior of historic building materials and material systems during and following floods.

1.2 Objective

The goal of this project was to produce results for comparison with Technical Bulletin 2, "Flood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program," issued by the Federal Emergency Management Agency (FEMA). Within the FEMA Technical Bulletin 2, Table 1 describes acceptable and unacceptable classes of materials numbered 1 through 5, with classifications 4 and 5 representing acceptable materials. The descriptions of these classes are used in Table 2 of Technical Bulletin 2 in order to classify a wide range of common, modern building materials. Absent from Table 2 are the specific historic materials examined in the present study, as well as classifications for constructed assemblies of multiple materials. The NPS is motivated to update the FEMA bulletin in order to recommend materials for retrofit and rehabilitation of historic structures at risk of severe flooding. Therefore, tests in this project should also evaluate the potential to dry and clean in-place materials for continued use after a flood.

1.3 Scope

The guidelines provided by FEMA in Table 1 of Technical Bulletin 2 require a wide matrix of test variables in order to fully classify the flood damage resistance of materials, including separate tests using either gray or black water, as well as either stagnant or moving water in the treatment vessel. In addition, the highest classifications require investigating the uptake of harmful pollutants, such as heating oil. However, the scope of the present study is limited. This project considers just one of the more severe treatment cases: moving, black water inoculated with mold and sewage surrogates representative of those found in natural floods, but lacking harmful pollutants. This single test case will provide the most useful information needed in order to classify materials of interest according to FEMA guidance to within reasonable error.

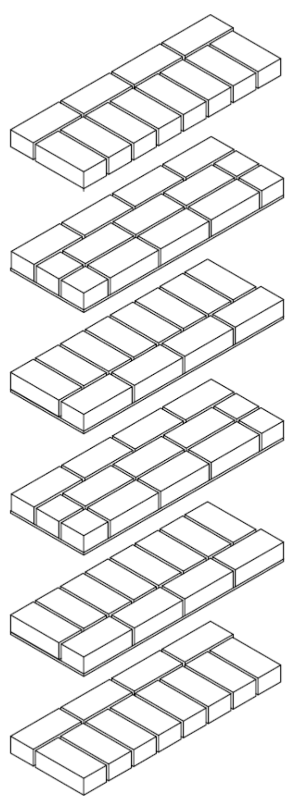
2 Specimen Descriptions

Three main groups of specimens are described in this section: brick walls, wood frame walls, and floors. Wall and floor specimens are lettered in order of project sponsor priority. Due to construction schedules and the flow of material procurement, the order of lettering did not necessarily match the chronological test schedule. Regardless, all proposed specimens were tested as described.

2.1 Brick walls (A, B, E, I, and J)

One brick wall was constructed using new 8x12x12-in. structural clay tile and a new extruded brick veneer with Portland-lime mortar. Four of the five brick walls were constructed using new handmade brick and lime putty mortar, intending to best simulate real historic structures without the expense and difficulty of sourcing reclaimed brick. Handmade brick walls were constructed of seven courses in three wythe common bond, as depicted in Figure 1. The walls were allowed to dry for a minimum of 4 weeks before commencing simulated flood tests.

Figure 1. Schematic representation of three wythe common bond orientation used for handmade brick walls in this project (seventh course omitted from drawing).



2.1.1 Wall A: Traditional brick assembly

Wall A is a handmade brick wall with lime putty mortar. Three nailing blocks made from reclaimed true-dimension lumber are substituted for bricks in the bottom two courses in order to attach a baseboard. The interior is three-coat plaster applied directly to the brick. After allowing 2 weeks of drying, the plaster and baseboard were coated with oil-based lead carbonate paint which was thinned using turpentine. The exterior is plain, exposed brick.

2.1.2 Wall B: Early twentieth century masonry assembly

Wall B is an extruded structural clay tile wall (8x8x12-in. tile; two courses) with an extruded brick veneer assembled using galvanized steel masonry ties and Portland cement and hydrated lime mortar. Nailing blocks made from new studs are fastened to the structural tile using toggle bolts in order to attach a baseboard. The interior is three-coat plaster applied directly to the structural tile. After allowing 2 weeks of drying, the plaster and baseboard were coated with oil-based lead carbonate paint which was thinned using turpentine. The exterior is plain, exposed brick veneer.

2.1.3 Wall E: Traditional brick assembly modified with insulation and gypsum wallboard interior

Wall E is a handmade brick wall with lime putty mortar. The interior veneer is constructed of nominal framing studs attached to the subfloor. The cavity between the framing studs and the brick is filled with insulating polyurethane spray foam. The wall is finished with gypsum wallboard, joint compound, primer, and latex paint. The exterior is plain, exposed brick.

2.1.4 Wall I: Traditional brick assembly with limewash

Wall I is a handmade brick wall with lime putty mortar. Three nailing blocks made from reclaimed true-dimension lumber are substituted for bricks in the bottom two courses in order to attach a baseboard. The interior is three-coat plaster applied directly to the brick. After allowing 2 weeks of drying, the plaster and baseboard were coated with oil-based lead carbonate paint which was thinned using turpentine. The exterior brick is whitewashed using lime putty thinned with water.

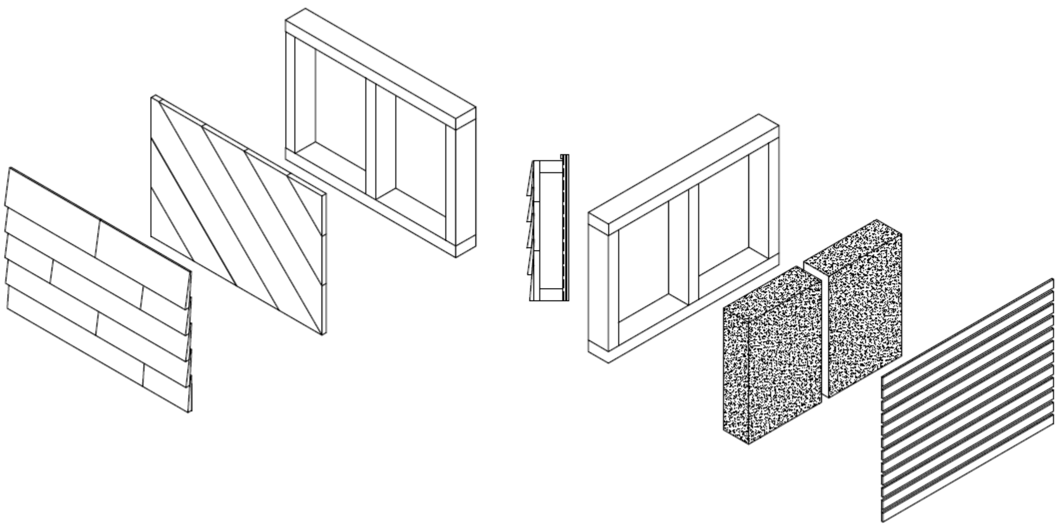
2.1.5 Wall J: Traditional brick assembly with wainscot

Wall J is a handmade brick wall with lime putty mortar. Two long sections of reclaimed true-dimension lumber are substituted for bricks in the second and fifth courses to serve as nailing blocks for the interior finishes of beadboard wainscot and baseboard. After allowing 2 weeks of drying, the wainscot and baseboard were coated with oil-based lead carbonate paint which was thinned using turpentine. The exterior is plain, exposed brick.

2.2 Wood frame walls (C, D, F, G, H, K, and L)

Figure 2 shows a schematic exploded diagram of a wood frame wall.

Figure 2. Schematic exploded diagram of an example wood frame wall (Wall H).



2.2.1 Wall C: Wood frame assembly lacking sheathing

Wall C is a reclaimed true-dimension lumber frame assembled using nails. The interior is three-coat plaster applied over reclaimed wood lath with a baseboard attached directly to the frame. The exterior is reclaimed German Cove (Dutch Lap) siding attached using 6d nails. After allowing 2 weeks of drying, the plaster, baseboard, and siding were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.2.2 Wall D: Wood frame assembly with sheathing

Wall D is a reclaimed true-dimension lumber frame assembled using nails. The interior is three-coat plaster applied over reclaimed wood lath with a baseboard attached directly to the frame. The exterior is reclaimed German Cove (Dutch Lap) siding attached over reclaimed oak diagonal sheathing using 6d nails. After allowing 2 weeks of drying, the plaster, baseboard, and siding were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.2.3 Wall F: Wood frame assembly with clapboard and wire lath

Wall F is a reclaimed true-dimension lumber frame assembled using nails. The interior is 2-coat plaster applied over self-furring metal lath with a baseboard attached directly to the frame. The exterior is reclaimed clapboard siding attached over reclaimed oak diagonal sheathing using 6d nails. After allowing 2 weeks of drying, the plaster, baseboard, and siding were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.2.4 Wall G: Wood frame assembly with aluminum siding

Wall G is a reclaimed true-dimension lumber frame assembled using nails. The interior is three-coat plaster applied over reclaimed wood lath with a baseboard attached directly to the frame. The exterior is reclaimed clapboard siding attached over reclaimed oak diagonal sheathing using 6d nails. Aluminum siding is attached directly over the clapboard without paint. After allowing 2 weeks of drying, the plaster and baseboard were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.2.5 Wall H: Wood frame assembly with mineral wool insulation

Wall H is a reclaimed true-dimension lumber frame assembled using nails. Mineral wool batt insulation fills the cavities between the framing boards. The interior is three-coat plaster applied over reclaimed wood lath with a baseboard attached directly to the frame. The exterior is reclaimed clapboard siding attached over reclaimed oak diagonal sheathing using 6d nails. After allowing 2 weeks of drying, the plaster, baseboard, and siding were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.2.6 Wall K: Wood frame assembly with stucco

Wall K is a reclaimed true-dimension lumber frame assembled using nails. The interior is 2-coat plaster applied over self-furring metal lath with a baseboard attached directly to the frame. The exterior is three-coat stucco applied over self-furring metal lath on reclaimed oak diagonal sheathing.

After allowing 2 weeks of drying, the plaster and baseboard were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.2.7 Wall L: Wood frame assembly with wainscot

Wall L is a reclaimed true-dimension lumber frame assembled using nails. The interior is reclaimed beadboard wainscot with a baseboard attached directly to the frame. The exterior is reclaimed clapboard siding attached over reclaimed oak diagonal sheathing using 6d nails. After allowing 2 weeks of drying, the plaster, baseboard, and siding were coated with oil-based lead carbonate paint which was thinned using turpentine.

2.3 Floors (A, B, C, and D)

2.3.1 Floor A: Heart pine

Floor A is constructed of reclaimed, 6x1-in. heart pine tongue-and-groove flooring which was not milled immediately prior to this test. The joist frame is reclaimed true-dimension lumber assembled using nails. Half of the floor is finished with oil-based floor wax, while the other half is finished with tung oil.

2.3.2 Floor B: Cypress

Floor B is constructed of reclaimed, 6x1-in. cypress tongue-and-groove flooring which was milled immediately prior to this test. The joist frame is reclaimed true-dimension lumber assembled using nails. Half of the floor is finished with shellac, while the other half is finished with tung oil.

2.3.3 Floor C: Ceramic tile

Floor C is constructed of new, 2x2-in. white ceramic tile. The slab is unreinforced limestone and Portland cement concrete. Tiles are set and grouted with Portland cement and lime mortar.

2.3.4 Floor D: Oak with sheathing

Floor D is constructed of reclaimed oak diagonal subfloor and reclaimed, 2x1-in. oak tongue-and-groove flooring which was not milled immediately prior to this test. The joist frame is reclaimed true-dimension lumber assembled using nails. The floor is finished with shellac.

3 Bill of Materials and Supplies

3.1 Building materials

Material and supply procurement was organized into five major classifications which are broken out in Table 1 through Table 4 below. Many of the supplies were sourced from the AbilityOne Program or General Services Administration (GSA) contract vendors. Some new and modern materials were sourced from Midwest distributors and home improvement retailers. Reclaimed materials were sourced from the Midwest, Great Plains, Southeast, and Northeast regions of the USA. These materials were used in as-received condition in order to best simulate field conditions. Some of the reclaimed materials arrived with existing coatings or evidence of existing mold (Figure 3). The siding coating compositions were analyzed in a scanning electron microscope with an energy-dispersive spectrometer (SEM-EDS), which determined that the existing coating on the German Cove (Dutch Lap) siding was lead-free, whereas the existing coating on the clapboard siding contained high quantities of lead.

Figure 3. Selection of new and reclaimed materials procured for this project, with evidence of existing mold and coatings on the two styles of reclaimed siding.

Table 1. Reclaimed and historical materials.

Walls	A	B	C	D	E	F	G	H	I	J	K	L				
Floors													A	B	C	D
Reclaimed true-dimension 2x4 lumber (frames, nailing blocks, joists)	X	X	X	X		X	X	X	X	X	X	X	X	X		X
Reclaimed diagonal board sheathing and subfloor				X		X	X	X			X	X				X
Reclaimed German Cove (Dutch Lap) siding			X	X												
Reclaimed clapboard siding						X	X	X				X				
Reclaimed wood baseboard	X	X	X	X		X	X	X	X	X	X	X				
Reclaimed beadboard for wainscot										X		X				
Williamsburg "Lead Oil Ground" paint w/ turpentine	X	X	XX	XX		XX	XX	XX	X	X	X	XX				
Reclaimed wood lath			X	X			X	X								
Graymont Niagara lime putty	X				X	X			X	X	X					
Reclaimed Heart Pine flooring													X			
Reclaimed Cypress flooring														X		
Reclaimed Oak flooring																X

Table 2. Ceramic materials.

Walls	A	B	C	D	E	F	G	H	I	J	K	L				
Floors													A	B	C	D
Cushwa Georgian handmade brick	X				X				X	X						
Extruded brick		X														
Structural clay tile (8x8x12-in.)		X														
Masonry ties		X														
Ceramic tile (2x2-in.)															X	

Table 3. Dry and powder materials.

Walls	A	B	C	D	E	F	G	H	I	J	K	L				
Floors													A	B	C	D
USG Red Top plaster	X	X	X	X		X	X	X	X		X					
Hydrated Lime		X									X				X	
Portland cement		X									X				X	
Masonry sand	X	X			X	X			X	X	X				X	
ASTM #67 limestone															X	

Table 4. Modern building materials.

Walls	A	B	C	D	E	F	G	H	I	J	K	L				
Floors													A	B	C	D
Self-furring metal lath						X					X					
Aluminum siding							X									
Nominal dimension lumber (framing and formwork)					X										X	
Nails (siding, framing, and lath)			X	X	X	X	X	X					X	X	X	
Finish nails (flooring, baseboard, and wainscot)	X	X	X	X	X	X	X	X	X	X			X	X		X
Toggle bolts		X														
Mineral wool insulation								X								
Spray foam (closed-cell PUR)					X											
Gypsum wallboard, joint compound, sandpaper, primer, and latex paint					X											
Shellac													X			X
Tung oil													X	X		
Floor wax (oil-based)														X		

3.2 Other materials and supplies

Apparatus supplies include a galvanized steel watering trough, vinyl tubing, bulkhead fittings, hose clamps, titanium water chiller, titanium water heater, water pump, 5-stage reverse osmosis system, water storage drums, and 5-gallon buckets. Apparatus containment chamber supplies include PVC pipe, PVC 3-way elbows, PVC tees, PVC cement, plastic sheeting, and cable ties. Biological materials and supplies include American Type Culture Collection (ATCC) starter cultures, potato dextrose broth, malt extract, sucrose, plating dishes, propagation flasks and incubator, cryopreservation vials, environmental sampling kits with Butterfield's solution, and insulated shipping containers. Cleaning and decontamination supplies include nitrile gloves, denatured ethanol, concentrated bleach, antimicrobial soap, spray bottles, microfiber towels, and bristle brushes. Construction supplies include plaster hawks, flat trowels, point trowels, paint measuring cups, paintbrushes, permanent markers, hammers, scoops, a wood saw, and a brick or tile saw.

4 Specimen Construction

4.1 Brick walls

Extruded and handmade bricks and tiles were used in as-received condition, except when it was necessary to brush off excessive dust. Partial bricks were cut using a diamond-tipped concrete saw. Lime mortars were mixed at an approximate volume ratio of 2.5 parts sand to 1 part lime putty with no added water. Portland-lime mortars contained about 3 parts sand to 1 part cement by volume, with lime added at 15% of the volume of cement. Limewash was produced using lime putty and water to create a proper consistency for coating applications. Figure 4 shows Wall B under construction.

Figure 4. Construction of Wall B.

4.2 Wood walls

Wood wall framing was constructed of reclaimed true-dimension lumber, as pictured in Figure 5. Walls were constructed in groups (Figure 6) in order to maximize labor efficiency. Wall interiors of three-coat plaster over reclaimed wood lath were constructed with appropriate keys and scoring in the scratch coat (Figure 7) and appropriate drying times between scratch, brown, and surface coat applications (Figure 8). Stucco for Wall K was prepared in a similar manner as Portland-lime mortars for Wall B.

Figure 5. True-dimension wood wall and floor joist framing.

Figure 6. Walls D, F, G, H, and K prepared for plaster and stucco application.

Figure 7. Plaster scratch coat application.

Figure 8. Plaster scratch coat with scoring allowed to dry.

4.3 Floors

Floor joist framing was constructed of reclaimed true-dimension lumber, as pictured in Figure 5. Figure 9 is a photograph of the sides of Floors A and D. The depth of penetration of tung oil into the heart pine of Floor A is visible forward in the frame and the diagonal sheathing construction of Floor D is in the background. Nails were added to the bottom of wood floor sections in order to meet the standard specification of spacing from the bottom of the treatment container, while maintaining the minimum specified depth below the simulated flood water line. Floor C was constructed of normal weight concrete with ASTM #67 limestone, graded sand, and Portland cement (Figure 10). After curing, four anchor bolts were sunk partially into the sides of the base to enable lifting of the specimen.

Figure 9. Floors A and D showing depth of penetration of tung oil finish.

Figure 10. Formwork containing the limestone concrete base of Floor C.

5 Experimental Procedures

5.1 Abridged ASTM E3075 – 16 specifications

5.1.1 Prior to immersion

1. Condition specimens in a controlled environment (75 ± 5 °F; 50 ± 5 % Relative Humidity) until equilibrium weight is observed by periodic weighing.
2. Record equilibrium weight, $W_{initial}$.
3. Treatment water shall conform to the following specifications: filtered potable tap water with 95% of chlorine and fluorides removed, pH 6.0 to 9.0, and temperature held at 75 ± 5 °F.

5.1.2 Test procedure

1. Add sewage surrogate, mold surrogates, and nutrient broth.
2. Immerse specimens for 72 to 80 hours. Vertical specimens must be immersed to 50 ± 10 % of their height. Horizontal specimens must be immersed such that no portion of the specimen is less than 1 inch below the water surface.
3. Place specimens on supports to lift them off the bottom of the treatment vessel.
4. Weights or other methods may be used to ensure floating specimens experience the desired immersion depth.

5.1.3 Drying

1. Measure specimen weight within 1 hour of removal (W_{wet}).
2. Dry specimens in a controlled environment (75 ± 5 °F; 50 ± 5 % Relative Humidity) until equilibrium weight is observed by periodic weighing.
3. Record the equilibrium final weight (W_{final}) and the time elapsed to achieve equilibrium final weight.

5.1.4 Cleaning and swabbing

1. Clean using microfiber cloth or a non-metal scrub brush using generally available anti-microbial soap and potable tap water, then rinse with potable tap water.
2. Assess surviving sewage and mold by swabbing on three surface locations according to standard practice ASTM D7789.

5.2 Biological sample and solution preparation

Sewage surrogate *Escherichia coli* and mold surrogates *Penicillium brevicompactum*, *Aureobasidium pullulans*, and *Eurotium herbariorum* were propagated from fresh starter culture according to nutrient and incubation specifications provided by ATCC. Culture samples were diluted, plated, and counted to determine cell and spore counts per milliliter. In order to achieve the concentrations specified in ASTM E3075 in each planned immersion test (see Appendix A for calculations), several 10 mL aliquots of *E. coli* and *P. brevicompactum* and several 2.5 mL aliquots of *A. pullulans* and *E. herbariorum* were prepared from bulk culture, then frozen at –80 °C. Aliquots were thawed in an ice bath for approximately 6 to 8 hours prior to an immersion test. Aliquots of *E. coli* were diluted 1/100 using Millipore water to achieve the specified concentration. Sterile pipette tips and an adjustable pipette precisely controlled the quantities of aliquots added to the immersion test solutions.

Solution preparation began 2 to 3 days prior to a test by first dissolving and autoclaving the correct quantity of potato dextrose broth (PDB) for the desired overall solution quantity (see Appendix A). Meanwhile, water storage drums were filled with 5-stage reverse osmosis treated water (RO water). Stored water was heated to 79 °F, anticipating some heat transfer to the colder trough and specimens, using a titanium aquarium heater. After thorough disinfection and purging (described below), the trough was filled with 40 to 45 gallons, or 80 to 90 gallons for a double batch, of RO water from the heated drums. The PDB was added, then the thawed fungi and bacteria were added to the trough near the pump inlet and allowed to circulate for 15 minutes prior to immersing specimens in the solution.

5.3 Apparatus construction and specimen immersion and removal

A galvanized steel watering trough with approximate dimensions 8x2x2-ft., having end radii of 12-in., was modified with small bulkhead ports at opposing corners to enable cross-flow of the treatment solution. Vinyl tubing connected one bulkhead to the pump inlet, which then led to a titanium aquarium chiller, after which the solution was carried to the other bulkhead and into the trough. Air bubbles were bled from the system by lifting the lines entering the chiller and by repeatedly tilting the chiller onto two of its feet. A titanium aquarium heater was submerged in the trough. Together, the heater and chiller maintained the specified water temperature of 75 ± 5 °F. A 10x3x3-ft. containment tent constructed from

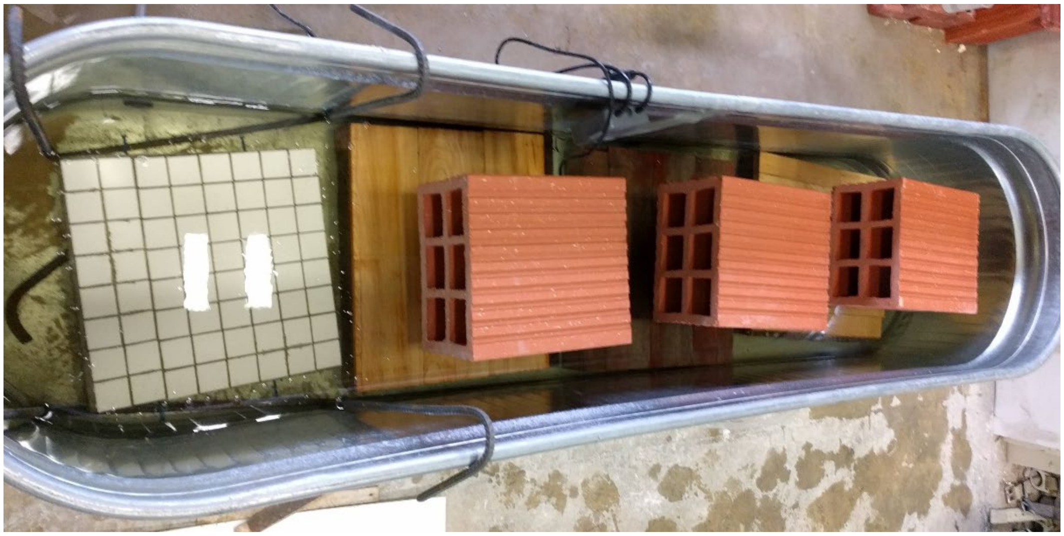
PVC pipe, PVC fittings, and plastic sheeting was placed over the apparatus to mitigate inward and outward contamination.

Specimens were lifted either by hand, or by an overhead crane and fabricated steel lifting hooks (Figure 11). Specimens were weighed before immersion. After 72 to 80 hours of immersion (Figure 12), specimens were removed, weighed, and set aside to dry. Tap water with 5% bleach was then sprayed onto the trough sides. In order to disinfect the treatment solution prior to pumping it to waste drains, 50 fl. oz. of bleach was added to each 40 gallons of treatment solution in the trough and allowed to circulate for at least 24 hours.

After pumping out the disinfected treatment solution, tap water with 5% bleach was added to further disinfect the apparatus. Soft bristle brushes and spray bottles containing 5% bleach solution were used to thoroughly disinfect the sides of the trough. The bleach solution was then pumped out while spraying the sides of the tank with potable tap water using a garden hose. After removing all of the bleach solution, tap water was used to purge the pump and chiller lines and remove any traces of bleach elsewhere on the trough. Then, RO water was poured down the sides of the trough in a cascading manner, so as to remove ions left behind by the tap water. Finally, the pump and chiller lines were purged using RO water, and the rmaining purge water was pumped out to waste drains.

Figure 11. Lifting Wall A into position at the beginning of Test 1.

Figure 12. Example test setup (Test 5) with brick and tile ballast holding floor sections under the water level.



5.4 Summary of experimental process

1. Dissolve and autoclave PDB
2. Stock and heat RO water
3. Pump out bleached treatment solution from previous experiment
4. Disinfect trough and lines with 5% bleach water and a brush
5. Pump out disinfecting bleach water
6. Hose down and clean tank with tap water
7. Purge 5% bleach water from pump, chiller, and lines using tap water
8. Pump out tap water
9. Pour RO water along tank sides
10. Purge tap water from pump, chiller, and lines using RO water
11. Pump out RO purge water
12. Thaw surrogate species in an ice bath
13. Add 40 gal (or 80 gal) of fresh RO water
14. Immerse and set up trough heater
15. Add PDB and surrogates to trough
16. Weigh and add specimens
17. Remove and weigh specimens
18. Add bleach to treatment solution and bleach spray the trough sides.

5.5 Swab collection

Surviving surrogates were sampled in accordance with standard practices set forth in ASTM D7789-12, “Standard Practice for Collection of Fungal Material from Surfaces by Swab.” A swab from a sterile Environmental

Sampling Kit with Butterfield's solution was dabbed at three locations on a surface, rubbing both vertically and horizontally as well as back and forth while slightly rotating the swab to ensure full coverage. Sample locations and surface materials were recorded and Chain of Custody forms were prepared. Finally, the sampling kits were packed in insulated boxes with an ice pack and sent to an external laboratory for analysis. Counts of sewage surrogate *E. coli* and total coliform are reported as the Most Probable Number (MPN). Counts of mold surrogates *P. brevicompactum*, *A. pullulans*, and *E. herbariorum* are reported in colony forming units (cfu) and colony counts.

5.6 Test schedule and abnormalities

The 12 walls and 4 floors were tested in 6 groups, each limited in specimen quantity by the size of the trough:

1. Walls B and I
2. Walls A and J
3. Walls C, D, and F
4. Wall G, H, and K
5. Floors A, B, C, and D
6. Walls E and L.

There were a few departures from standard procedures to report:

1. Test 1 was under-filled with a 40-gal. batch size, so displacing bricks were used to raise the water level to above the top of the baseboard. The remaining tests, except Test 5, used 80-gal. batch sizes.
2. At some time during Test 4, the duct tape holding Walls H and G vertically failed, allowing Walls H and G to tilt about 10 to 15 degrees toward their interior sides (Figure 13).
3. At some time during Test 5, the pump flow was blocked by a pinched hose. The lack of flow to the chiller resulted in a treatment temperature of 80 °F, which remained within specification. Flow and chilling to 75 °F were restored for the final 8 hours of treatment.

Figure 14 shows the typical appearance of the treatment solution after the removal of test specimens.

Figure 13. Photograph taken at the completion of Test 4.

Figure 14. Typical appearance of treatment solution after removing specimens.

6 Results and Discussion

6.1 Specimen photographs after treatment

6.1.1 Brick walls

The photographs in Figure 15 through Figure 24 show the brick wall specimens after treatment.

Figure 15. Photograph of Wall A exterior after treatment.

Figure 16. Photograph of Wall A interior after treatment.

Figure 17. Photograph of Wall B exterior after treatment.

Figure 18. Photograph of Wall B interior after treatment.

Figure 19. Photograph of Wall E exterior after treatment.

Figure 20. Photograph of Wall E interior after treatment.

Figure 21. Photograph of Wall I exterior after treatment.

Figure 22. Photograph of Wall I interior after treatment.

Figure 23. Photograph of Wall J exterior after treatment.

Figure 24. Photograph of Wall J interior after treatment.

6.1.2 Wood frame walls

The photographs in Figure 25 through Figure 36 show the wood frame wall test specicimens after treatment.

Figure 25. Photograph of Wall C exterior after treatment.

Figure 26. Photograph of Wall C interior after treatment.

Figure 27. Photograph of Wall D exterior after treatment.

Figure 28. Photograph of Wall D interior after treatment.

Figure 29. Photograph of Wall F exterior after treatment.

Figure 30. Photograph of Wall F interior after treatment.

Figure 31. Photograph of Wall G exterior after treatment and disassembly.

Figure 32. Photograph of Wall H cavity after treatment and disassembly.

Figure 33. Photograph of Wall K exterior after treatment.

Figure 34. Photograph of Wall K interior after treatment.

Figure 35. Photograph of Wall L exterior after treatment.

Figure 36. Photograph of Wall L interior after treatment.

6.1.3 Floors

The photographs in Figure 37 and Figure 38 show the floor test specimens after treatment.

Figure 37. Photograph of Floors A, B, and D after treatment.

Figure 38. Photograph of Floor C after treatment.

6.2 Specimen weight logs

The ASTM E3075 standard requires periodic weighing of specimens in order to determine equilibrium and maximum weights at critical time points. Line plot logs of specimen weight are grouped into three inconsequential sets in Figure 39 through Figure 41 for ease of discerning each line. As required by the standard, the dry weight, wet weight, percent increase in weight after immersion, final weight, and days to final weight are provided in Table 5. Final weights and days to final weight are reported as of the time of swab collection. The wet weight of Wall L is artificially low due to an error of the equipment used to weigh the specimen. The drying time of Wall J is artificially high compared with other brick walls due to a lapse in the ability to weigh Wall J during drying.

Figure 39. Weight log of Walls A, B, E, I, and J.

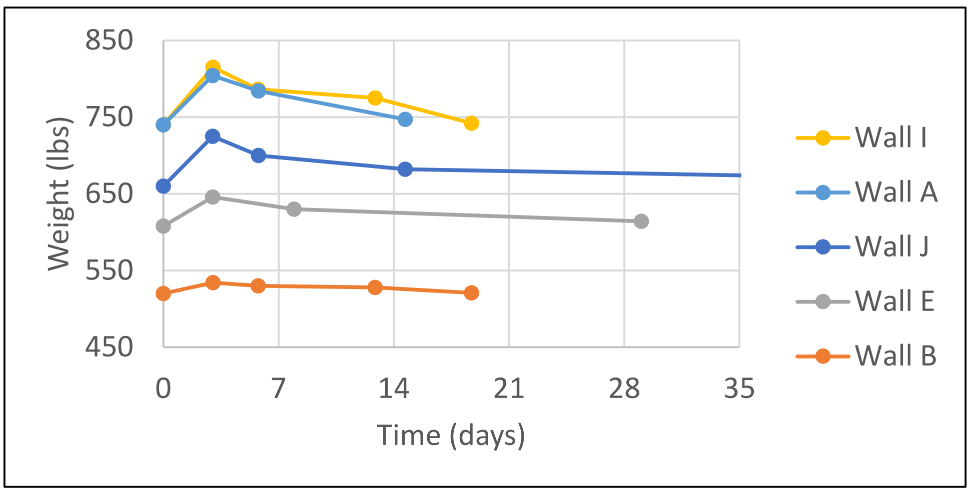


Figure 40. Weight log of Walls C, D, F, G, H, and K and Floor C.

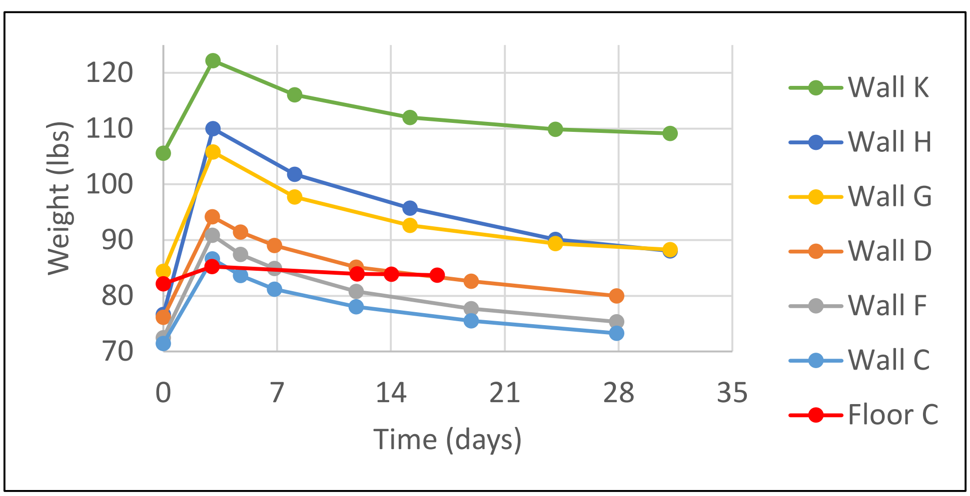


Figure 41. Weight log of Wall L and Floors A, B, and D.

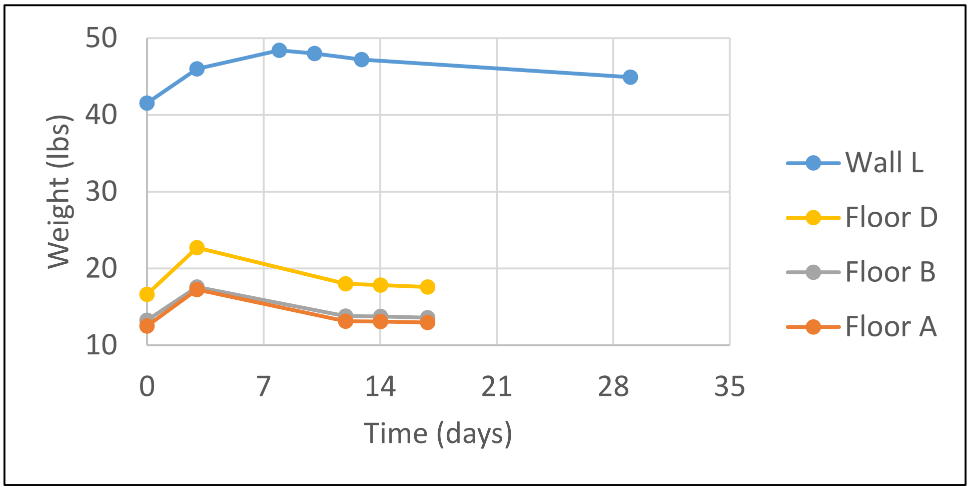


Table 5. Enumerated weight log as required by ASTM E3075. (*Wall L wet weight is incorrect due to an equipment error).

Walls	A	B	C	D	E	F	G	H	I	J	K	L				
Floors													A	B	C	D
Dry weight	740	520	71.5	76.2	608	72.5	84.4	76.7	740	660	106	41.6	12.5	13.3	82.2	16.7
Wet weight	804	534	86.6	94.2	646	90.9	106	110	815	725	122	46*	17.3	17.6	85.3	22.7
% increase	8.6	2.7	21.1	23.6	6.3	25.3	25.6	43.6	10	9.8	15	*	38.4	32.3	3.8	35.9
Final weight	747	521	73.3	80.0	614	75.4	88.3	88.1	742	660	109	44.9	13.0	13.6	83.7	17.6
Days to final	15	19	28	28	29	28	31	31	19	71	31	29	17	17	17	17

6.3 Swab results

A total of 112 swab samples, 56 each for *E. coli* and fungi analysis, were collected and analyzed. An external lab, selected through solicitation W9132T18T0057, "FUNGAL AND BACTERIAL SWAB ANALYSIS," carried out analysis of all swabs. Within three days of receipt of swabs, the laboratory performed, "Colilert MPN by Modified SM9223B (MICRO-SOP-100)," to determine the MPN of viable *E. coli* and total coliform. Fungal swabs were analyzed according to the, "MICRO-SOP-202," method. Due to limited analytical sensitivity, the contractor reported all fungal test results as 100 cfu per swab. Reported colony counts are tabulated below in order to provide more information to the reader, but these results may not be statistically relevant for comparison with each other (see Table 6, Table 7, and Table 8). All swab locations are below the simulated flood water line, except where noted.

We additionally performed viability plating tests on solutions collected after the end of Test 6. Fungal plates returned 2x10^4 spores per liter, while coliform plates returned 5x10^5 cells per liter. These results confirm the presence of adequate quantities of viable biological matter in the treatment solution at the end of a test.

6.3.1 Tables of swab test results

Table 6. Brick wall swab test results.

Wall	Location	Description	Swab	*E. coli* MPN	Total coliform	Fungal colony count
A	Exterior	Handmade brick (below water)	1	<1	<1	1
	Interior	Painted plaster surface	2	<1	<1	<1
	Interior	Painted baseboard surface	3	<1	>2419.6	1
	Interior	Handmade brick (behind baseboard)	4	<1	<1	3
	Exterior	Lime-based mortar	5	<1	<1	1
B	Exterior	OPC mortar	6	<1	<1	<1
	Exterior	Extruded brick	7	<1	<1	<1
	Interior	Between clay tile and extruded brick	8	<1	<1	<1
	Interior	Painted plaster surface (above water)	9	<1	<1	<1
	Interior	Extruded brick (behind baseboard)	10	<1	<1	5
E	Exterior	Handmade brick (above water)	17	<2	21.8	1
	Interior	Wallboard (behind baseboard)	18	305.8	551.0	2
	Interior	Foam insulation (behind wallboard)	19	3106.2	>4839.2	6
	Interior	Handmade brick (behind foam)	20	>4839.2	>4839.2	2
	Interior	Painted wallboard surface	21	52.4	471.8	4
I	Exterior	Limewash surface on handmade brick	33	<1	<1	3
	Exterior	Limewash surface on lime-based mortar	34	<1	<1	<1
	Interior	Painted plaster surface	35	<1	<1	<1
J	Interior	Painted wainscot surface	36	<2	42.6	<1
	Interior	Painted baseboard surface	37	<2	80.8	8
	Interior	Wainscot (behind baseboard)	38	<2	>4839.2	1

Table 7. Wood frame wall swab test results.

Wall	Location	Description	Swab	*E. coli* MPN	Total coliform	Fungal colony count
C	Exterior	Painted German cove siding	11	<1	<1	1
	Exterior	German cove siding (interior face)	12	2.0	>2419.6	2
	Cavity	Plaster and wood lath in cavity	13	1732.9	>2419.6	2
D	Exterior	Painted German cove siding	14	<1	<1	<1
	Exterior	Diagonal sheathing (behind siding)	15	<1	>2419.6	4
	Cavity	Plaster and wood lath in cavity	16	6.3	>2419.6	<1
F	Exterior	Painted clapboard siding	22	<1	<1	<1
	Exterior	Diagonal sheathing (behind siding)	23	1.0	>2419.6	1
	Interior	Painted plaster surface (above water)	24	<1	<1	<1
	Interior	True-dimension lumber (above water)	25	16.1	920.8	1
G	Exterior	Aluminum siding surface	26	<1	3.1	3
	Exterior	Clapboard siding (behind aluminum)	27	<1	<1	<1
	Interior	Painted plaster surface (above water)	28	<1	<1	<1
H	Exterior	Painted clapboard siding	29	<1	1.0	<1
	Exterior	Mineral wool insulation	30	<1	>2419.6	2
	Cavity	Plaster and wood lath in cavity	31	<1	>2419.6	1
	Interior	Painted plaster surface (above water)	32	2.0	20.1	<1
K	Exterior	Stucco surface	39	<1	<1	1
	Interior	Painted plaster surface	40	<1	<1	3
	Interior	Plaster surface (behind baseboard)	41	<1	1.0	<1
L	Exterior	Painted clapboard siding	42	<2	12.6	1
	Exterior	Diagonal sheathing (behind siding)	43	2.0	>4839.2	1
	Interior	Painted wainscot surface	44	<2	<2	1
	Interior	Wainscot (behind baseboard)	45	<2	>4839.2	<1

Table 8. Floor and control swab test results.

Floor	Location	Description	Swab	*E. coli* MPN	Total coliform	Fungal colony count
A	Top	Floor wax	46	<1	105.4	1
	Top	Tung oil	47	<1	387.3	<1
B	Top	Shellac	48	<1	2.0	<1
	Top	Tung oil	49	<1	1.0	<1
C	Top	Ceramic tile surface	50	<1	<1	<1
	Top	Grout surface	51	<1	<1	<1
	Middle	Base after removing tile	52	<1	<1	<1
D	Top	Shellac	53	<1	3.1	<1
	Middle	Subfloor (under flooring)	54	18.1	>2419.6	4
CTL1	As-received	True-dimension lumber	55	<1	<1	1
CTL2	As-received	German cove siding	56	<1	<1	<1

7 Recommendations

7.1 Results in context of FEMA Technical Bulletin 2

The FEMA Technical Bulletin 2 material class descriptions categorize five levels of resistance to flood damage. Classes 1, 2, and 3 are deemed unacceptable for support by FEMA, while classes 4 and 5 are deemed acceptable. Class 1 is not resistant to any type of moisture damage. Class 2 is not resistant to clean water damage, but may survive moisture damage. Class 3 is not resistant to contaminated flood water damage, but could dry for reuse after clean water damage. Class 4 is resistant to flood water damage, but only in still or slowly moving floods. Class 5 is highly resistant to floodwater damage, including that caused by moving water.

In the tests reported here, most new ceramic and hard materials (Wall B, Floor C) took on little water and cleaned easily, returning <1 MPN and cfu in swab tests. Surfaces coated with lead-based paint also fared well, except where the paint had peeled. Specimens containing porous materials, such as plaster and lime-based mortar, required significantly longer drying times. The flood solution tended to wick upward above the flood water line, especially within plaster, lime mortar, and wood frames (Figure 42). The mineral wool insulation held the most water by far and was not able to dry within the allotted time frame of the project, but the closed-cell spray foam (Wall E, Figure 43) performed well, despite high counts of surviving mold and bacteria. Cavities, subfloors, surfaces behind baseboards, and sheathing all showed high coliform activity and/or fungal counts due to the lack of physical access during cleaning. Considering these results, recommended classifications of materials tested during this project are provided in Table 9.

Figure 42. Photograph of Wall C, D, and F frames showing wicking of the treatment solution and subsequent mold growth during the drying phase.

Figure 43. Photograph of Wall E cavity showing resilience of spray foam insulation.

Table 9. Recommended material classifications.

Material	FEMA Class	Recommended Class	Comment
True-dimension lumber	4	3	Wicking above water line
Diagonal sheathing	3	2	High water retention
Dutch lap siding	3	3	Concur with FEMA
Clapboard siding	3	3	Concur with FEMA
Wood baseboard	3	3	Harbors hidden biological activity
Wood beadboard	3	1	Warps easily
Lead Oil Ground paint	N/A	1	Provides biological resistance, but peels off
Wood lath	3	2	Wicking above the water line
Lime putty (mortar)	N/A	1	Extreme wicking and loss of strength
Lime putty (limewash)	N/A	4	Excellent durability and biological resistance
Heart pine flooring	1	3	Requires refinishing to remove biological activity
Cypress flooring	1	3	Requires refinishing to remove biological activity
Oak flooring	1	1	Sheathing and shellac caused major damage
Ceramic flooring	4	5	Excellent performance
Handmade brick	N/A	4	Porosity could harbor biological activity
Extruded brick	4	5	Excellent performance
Clay tile	5	5	Excellent performance
Plaster	3	1	Extreme wicking, cracking, and destruction
Portland cement	5	3	Staining from PDB due to porosity
Metal lath	4	4	Potential for corrosion and discoloration
Aluminum siding	3	3	Difficult to fully remove biological activity
Mineral wool insulation	3	1	Extreme wicking and water retention
Spray foam insulation	5	3	
Gypsum wallboard	3	2	Extreme wicking and cracking
Shellac	N/A	1	Discoloration
Tung oil	N/A	3	Requires refinishing to remove biological activity
Floor wax	N/A	3	Requires refinishing to remove biological activity

7.2 Recommended improvements to the experimental process

- Install steel lifting handles on wood frame walls prior to measuring their initial weight.
- Improve the base and lifting system for brick walls.
- Attach steel ballast under wood frame wall and floor specimens.
- Use multiple, smaller storage drums for RO water, or an improved storage tank and pumping system.
- Use nylon-reinforced vinyl tubing to prevent hose kinks.
- Significantly increase the curing time allotted for lime-based mortars and plaster (1 year or more).
- Implement drying conditions which better mimic those found after a major flood (generally more humid, possibly warmer), though this may significantly increase the time to dry.
- Swab specimens both before and after drying in order to capture more precise coliform counts. The relatively low inoculation concentration and far from optimal incubation conditions may cause artificially low *E. coli* counts after drying.
- Include tests for individual materials of interest. Wall and floor assembly tests are instructive for specific scenarios (Figure 44). However, individual material tests can better control variables and improve the accuracy of conclusions about specific materials.

Figure 44. Photograph of Wall D cavity after drying, showing heavy contamination.

References

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Appendix A: Inoculation calculations

Tank Inoculation

- Tank volume 40 gal = 151 L
- Target concentration of each species 10^6 MPN/CFU L^{-1}

$10^6 \times 151 = 1.51 \times 10^8$ cells, spores / Tank

1. E. coli 8-2-18 7.7×10^{10} cells/mL = 7.7×10^7 cells/uL

$\frac{1.51 \times 10^8}{7.7 \times 10^7}$ = (1.96 ul) Dilute 1/100 add (196 ul)

2. A. pullulans 8-7-18 7.6×10^7 spores/mL = 7.6×10^4 spores/uL

4 x 10 mL $\frac{1.51 \times 10^8}{7.6 \times 10^4}$ = 1986.8 ul = (2 mL)

3. P. brevicompactum 8-7-18 3.3×10^8 spores/mL = 3.3×10^5 spores/uL

10 x 10 mL $\frac{1.51 \times 10^8}{3.3 \times 10^5}$ = (457.6 ul)

4. E. herbariorum 8-7-18 7.5×10^7 spores/mL = 7.5×10^4 spores/uL

5 x 10 mL $\frac{1.51 \times 10^8}{7.5 \times 10^4}$ = 2013.3 ul = (2 mL)

5. PDB = 0.1% (w/v) = 1 g/L = 151 g / Tank

75.5 g/L 2L for each tank (experiment).

1-14-19

— A. pullulans and E. herbariorum were thawed on ice combined and realiquoted in 2.5 mL volumes. This was done so the same batch of cultures can be used for all experiments (without freeze-thaw more than once).

— PDB Made 2L of 75.5 g PDB. Add all for each exp. (151 g/Tank). Autoclaved 15 min. 120 °C.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE (DD-MM-YYYY) May 2019	**2. REPORT TYPE** Final	**3. DATES COVERED (From - To)**

4. TITLE AND SUBTITLE Flood Resilience of Traditional Building Materials: Report of simulated flood immersion according to ASTM E3075 standard procedures	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Peter B. Stynoski, Thomas A. Carlson, Abigail M. Brake, Clint M. Arnett, Marion L. Banko, and Matthew M. Landi	**5d. PROJECT NUMBER** 473944
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL) 2902 Newmark Drive - PO Box 9005 Champaign, IL 61826-9005	**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/CERL TR-19-8
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Park Service Washington, DC 20240	**10. SPONSOR/MONITOR'S ACRONYM(S)** NPS
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Following the directives of the Secretary of the Interior's Standards for the Treatment of Historic Properties and the FY18-22 United States Army Corps of Engineers Campaign Plan, the National Park Service Technical Preservation Services and the United States Army Construction Engineering Research Laboratory collaborated on a project titled, "Resilience of Traditional Materials." The team sourced materials for, constructed, and tested five brick wall assemblies, seven wood frame wall assemblies, and four floor assemblies in simulated flood conditions according to standard procedures set forth in ASTM E3075-16, "Standard Test Method for Water Immersion and Drying for Evaluation of Flood Damage Resistance." The results helped the team to classify historical building materials in the context of Federal Emergency Management Agency guidelines for flood resistance. In general, most materials performed as expected, but further work is required in order to fully characterize individual materials and different types of flood conditions.

15. SUBJECT TERMS
Floods, Flood control, Flood damage prevention, Floods--Risk assessment, Building materials, Historic buildings, Structural design

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	54	**19b. TELEPHONE NUMBER**