Conservation of Dalle de Verre at the New York Hall of Science

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The conservation of more than 5,000 concrete dalle-de-verre panels in a structure built for the 1964 World's Fair reanimated a luminous construction designed to inspire space exploration.

The New York Hall of Science was constructed for the 1964-1965 New York World's Fair as the New York Museum of Science and Technology. Designed by Wallace K. Harrison of the architectural firm Harrison and Abramowitz, it was one of the many fair buildings that reflected America's infatuation with space during the 1960s.[1] Unlike most fair buildings, which were subsequently demolished, the Hall of Science was planned as a permanent museum and stands today as a landmark of mid-century design.

The primary exhibition space in Harrison's design, referred to as the Great Hall, is a 90-foot-high, single-story tower, which is set on a hexagonal plinth.[2] The facade of this tower consists of a reinforced-concrete grid, delineated by concrete columns and beams, which encloses approximately 5,400 cells (Fig. 1). Each cell is filled with a handcrafted dalle-de-verre panel; each panel is comprised of 1-inch-thick reinforced precast concrete and approximately 20 cobalt blue glass polygons of varying sizes. The panels were designed and manufactured by Willet Studios of Philadelphia and were originally coated with epoxy. The cast-in-place concrete grid and the dalle-de-verre panels (which are referred to in this article as simply cast-in-place concrete and panels) together result in a nearly flush exterior facade, while the interior has deep coffers. The light penetrating the translucent blue glass within the multistory, dark, free-form hall is intended to evoke the feeling of journeying through the cosmos (Fig. 2).

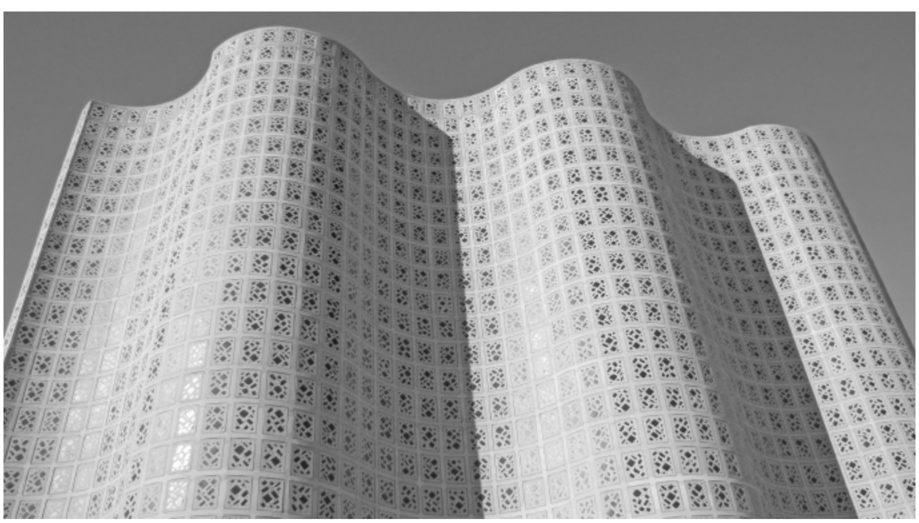

Fig. 1. New York Hall of Science, Queens, New York, built in 1965, exterior facade of the Great Hall in 2013. The dalle-de-verre panels are set in a cast-in-place concrete matrix. All images by the authors.

A reflecting pool with running fountains originally surrounded the perimeter of the Great Hall. The light bouncing off the rippling water in these fountains and pools further enhanced the sense of movement within the building. The fountains were interrupted by a walkway only at the hall's entrance, which was formed by an overlap in the undulating walls; there, visitors passed through revolving doors into the exhibition space (Fig. 3).[3]

Models of two aerospace taxis and an orbiting space laboratory, precursors to the U.S. Space Shuttle and Skylab, initially hung from the ceiling of the Great Hall.[4] They were part of a multimedia show, entitled "Rendezvous in Space," which employed a motion picture and sound effects to simulate a docking of the taxi to the laboratory.[5] These models, as well as the film screen, were removed long ago, but the multistory dalle-de-verre construction continues to awe museum visitors.

In 2005 the authors joined the Great Hall restoration team as consultants for the repair of the cast-in-place concrete and panels. An exterior restoration campaign was designed to address the cracks and spalls in the cast-in-place concrete of the facade, which had resulted from corrosion of steel reinforcement that had

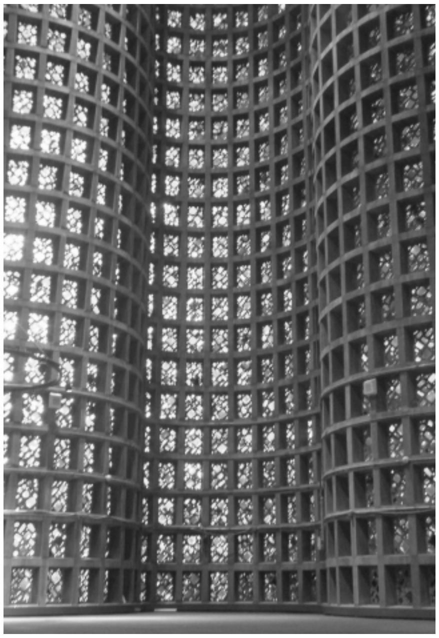

Fig. 2. Interior of the Great Hall before the interior upgrade, 2010.

been installed with inadequate concrete cover. Treatments were also designed for the friable, weathered surfaces of the panels in an attempt to extend their life. Panels that were beyond repair were replaced with new dalle-de-verre panels made of epoxy and stained glass. The significance of the Hall of Science is largely due to the visual impact of the dalle de verre. The restoration of the panels demanded thorough testing and careful application of repair strategies and coatings.

This paper focuses on the work associated with the restoration of the panels. A brief history of the panels and their installation is provided. The results of laboratory and on-site testing are described; this testing was performed in order to develop a system for repairing and coating the cracked and friable panels. The tests performed to review the impact associated with applying protective coatings over the glass are also explained. The restoration work, including the need to produce special tools to implement the selected strategies and precautions that were necessary to protect the art glass during coating applications, is explained.

Manufacturing Dalle de Verre for the Hall of Science

Dalle de verre is a twentieth-century material developed in the late 1920s and early 1930s that employs slabs of glass ("dalles"), usually about 1 inch thick. Dalles are typically chipped, or faceted, to produce variations in light transmission. Early dalle de verre consisted of glass slabs set in a reinforced-concrete matrix. The popularity of dalle de verre during this period was partially due to the ability to produce large installations of translucent glass in less time than traditional stained glass. The aesthetics of the materials and resultant designs, which used readily available concrete, were also suited to the aesthetics of Modernism.[6]

While Europeans continued to work to perfect the use of concrete as a matrix for dalle de verre, Americans embraced new epoxy technologies. During the 1960s American studios shifted to using an all epoxy, rather than concrete, matrix.[7] Although epoxy-matrix dalle de verre was being produced by the time the Hall of Science was constructed, Wallace Harrison instead chose to install concrete panels with an epoxy coating. It is unclear if this choice was made out of a preference for the aesthetics of the concrete, concern over the longevity of the new epoxy-matrix technology, or financial constraints.[8]

The dalle-de-verre panels at the Hall of Science are approximately 1 inch (2.54 centimeters) thick, 23½ inches (59.7 centimeters) wide, and 33 inches (83.8 centimeters) high. The Blenko Glass Company of Milton, West Virginia, specially cast the 1-inch-thick pot-metal glass in 8-inch (20.3-centimeter) squares.[9] Some of these squares were used whole, but most were hand cut to a variety of dimensions, some less than 1 inch square. Larger pieces were conchoidally chipped to add a prismatic effect to the glass. Willet Studios produced the panels by setting the glass and the ferrous-wire reinforcement in a matrix of concrete mixed from Corson's Home-Crete Sand Mix.[10] Five different shades of faceted cobalt blue glass dalles were used in the panels. Small ruby, gold, and green dalles accent some of the panels. Harrison's design called for only blue glass, but Willet Studios adamantly argued for the inclusion of these additional colors. Harrison eventually agreed, although he insisted that the manufacturer employ the other colors sparingly.[11]

Willet Studios applied two coats of Benesco epoxy resin to the concrete-and-glass panels for waterproofing after the concrete matrix had fully cured. A third and final coat of epoxy was reportedly applied to the entire facade to form a skin over the exterior surface of the panels and the cast-in-place concrete.[12] Bob Benes developed Benesco epoxy around 1960 as a setting compound for glass dalles; it was the first epoxy designed specifically for use as a dalle-de-verre matrix.[13] However, the process of coating concrete dalle de verre with Benesco epoxy appears to have been rarely used. Willet Studios worked seven days a week for nearly a year to produce the Hall of Science's approximately 5,400 panels. Each panel was designed to differ slightly from surrounding panels.[14]

After curing and waterproofing, each panel was subjected to laboratory test-

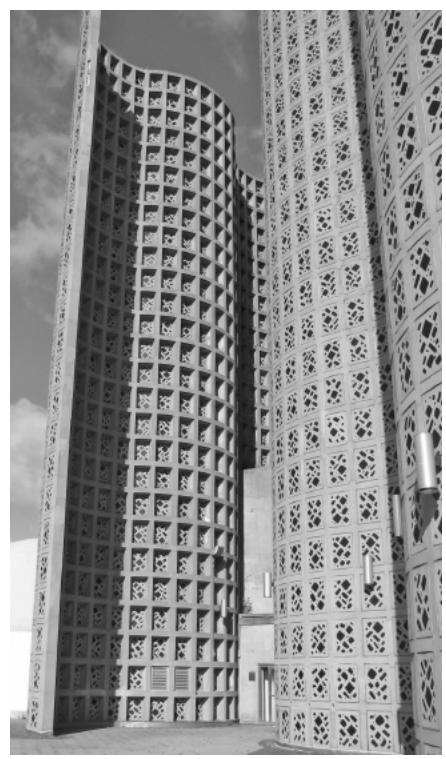

Fig. 3. The free-standing concrete wall at the left overlaps the undulating wall that encloses the tower, 2006. The entrance to the Great Hall is located below the solid concrete wall visible at the center of the photograph.

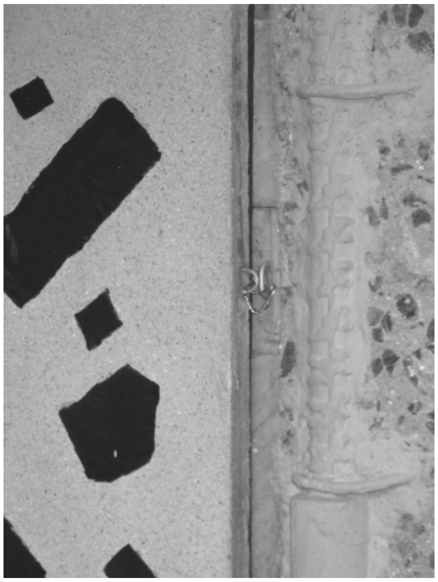

Fig. 4. Attachment of dalle-de-verre panel to cast-in-place concrete, 2010. The concrete on the left side of the image was demolished, and the steel reinforcement was cleaned and coated with a rust-inhibitive coating in preparation for patching.

ing. Wind with up to 25 pounds per square foot of static pressure was applied. Water was sprayed on the exterior surfaces while a vacuum was created on the opposite side. This process was intended to simulate the power of 100-mile-per-hour winds. Having passed these tests, the panels were installed at the Hall of Science.[15]

Each panel was attached to the cast-in-place concrete grid at two locations along each long edge of the panel. Stainless-steel loops were embedded in the cast-in-place concrete and in the panel. Stainless-steel wire ties were used to attach the panel and framework to one another (Fig. 4). The panels were set on neoprene setting blocks, and a continuous neoprene gasket was secured around the perimeter of each panel. Sealant was used in the approximately 5/8-inch joint around each panel.

At the time of construction, with more than 30,000 square feet of glass, the Hall of Science was reputed to be the largest dalle-de-verre installation in the world.[16] When the Great Hall finally opened on September 9, 1964, Ada Louise Huxtable, the architecture critic of the *New York Times*, described the effect as follows: "Here, one thinks immediately of the 13th century rather than the 20th; of Sainte-Chapelle; of the drama of soaring heights stained with colored light. For this is a Cathedral of Science, rather than a Hall of Science, its luminous blue walls suggesting limitless extensions of space. At a time when science vies with religion in explaining the mysteries of the universe, this is an oddly significant architectural twist."[17]

Characterization of the Precast Concrete Matrix

Corson's Home-Crete Sand Mix is no longer available. To better understand this material and the condition of the panels, petrographic and chemical analyses were performed on samples taken from a panel that was removed from an exterior wall of the Great Hall.[18] The concrete is characterized as a fly-ash-modified, gray portland-cement-based matrix with light brownish gray, fine-grained quartz aggregate. The sand-to-dry-binder ratio is estimated 4:1 by weight; the fly ash is estimated to represent a 19 to 27 percent replacement of portland cement by weight. The aggregate is moderately well graded with a relatively low abundance of fines. No air entrainment or pigments were identified in the panels.[19]

The components of the panel were well mixed and consolidated. The matrix is hard and dense due to the hydrated binder that resulted from the pozzolanic reaction of the fly-ash addition. The binder has weathered between the grains of sand at the surface. Between these sand grains, microscopically thin patches of leached paste are visible; this condition is characteristic of acidic weathering.[20]

It was also determined that the sample panel was carbonated to a depth of 9 millimeters from the exterior surface of the panel and 4 millimeters from the interior. Only 1 millimeter of carbonation was found at the concrete laterally adjacent to glass. This depth of carbonation is not unusual for concrete that is more than 40 years old. The wire reinforcement is composed of steel wire approximately 2.4 millimeters in diameter set approximately 6.4 millimeters from the outer surface of the panel. Because embedded steel wires at isolated areas are within the outer carbonated section of concrete, they are susceptible to rusting. Minor corrosion was visible.[21]

Characterization of Panel Coatings

Inside the lobby of the Great Hall original panels that were set flush with the cast-in-place concrete exhibited a translucent yellow film coating their surface (Fig. 5). The film was found to be flaking from the glass, as well as from the precast concrete. On the exterior of the building, small flakes of this brittle material could be seen on panels in areas protected from weathering due to the presence of the free-standing wall that overlaps part of the facade. The coating apparently weathered more on surfaces with greater exposure to the elements.

Samples of the coating were removed from interior panels and subjected to Fourier transform infrared spectroscopy (FTIR). The infrared spectra of this coating exhibited features consistent with a mixture of materials, including epoxy and a phthalate-based material. Phthalates are used to plasticize certain polymers (including epoxy) but are also are used to make alkyd resins. It is not known if the phthalate was used as a plasticizer in epoxy, in a mixture of epoxy and alkyd, or in both. A cross section of the coating that was examined using fluorescence microscopy revealed a single discernible layer of the material.[22] This layer is likely the Benesco epoxy applied by Willet Studios as a waterproofing material.[23] Benesco was formulated for making cast panels, and it is possible that it was modified with a plasticizer to make it flow better as a coating.[24]

Fig. 5. Translucent coating degrading on interior dalle-de-verre panel, 2009.

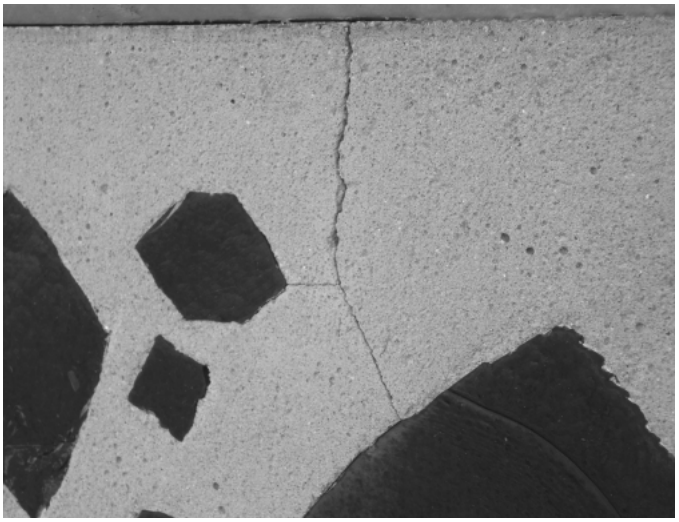

Fig. 6. Typical crack in a dalle-de-verre panel, stretching from glass to the edge of the panel, 2009.

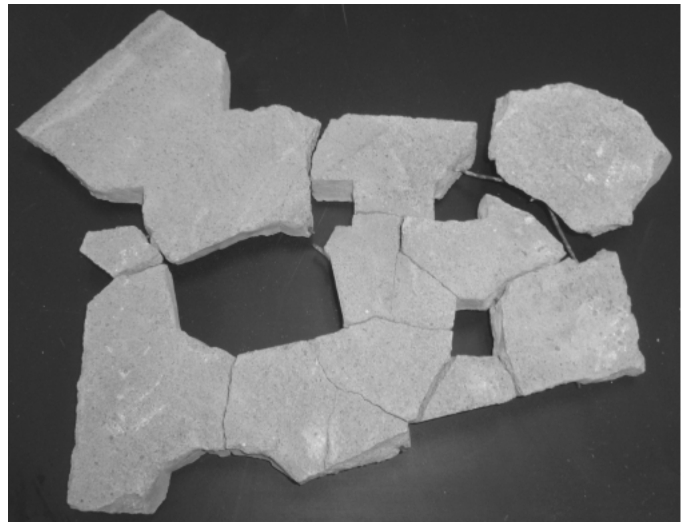

Fig. 7. Deteriorated panel that was broken apart in order to test the concrete and glass, 2009. Steel reinforcement made it difficult to separate the concrete fragments.

Deterioration of the Dalle de Verre

Cracks radiate from some of the glass dalles to the concrete edges of the panels and are common at locations where wire ties were embedded for attachment to the cast-in-place concrete (Fig. 6). Many of these cracks penetrate the full depth of the panel and are visible on the interior of the building. These cracks, as well as spaces in between the dalles and the matrix, allow water penetration through the panels and contribute to water staining on the interior surfaces. Some panels have also been punctured by electrical, mechanical, and security equipment. The wire reinforcement in the panels successfully holds together the most severely cracked panels (Fig. 7).

Close-up inspection indicated that the surfaces of the panels were friable: the aggregate and matrix lacked cohesion. Severe erosion of the panel surfaces in isolated locations exposed the ferrous-metal reinforcement, which exhibited corrosion.[25]

The surfaces of the panels generally exhibited light general atmospheric soiling. Darker stains were noted at the parapet level and near the bottom of panels at the base of the building. Heavy biological growth was also noted, primarily at the parapet level and on the north elevation. The interior faces of the panels exhibited general soil and dust deposition. Stains were typically due to water infiltration around the glass dalles, at deteriorated sealant, and through cracks in the panels.

Although the focus of the dalle-de-verre conservation addressed the precast concrete matrix, isolated cracks in the glass dalles were also examined and considered. The majority of the glass was in good condition. No evidence of glass deterioration due to alkali reactions was observed at the perimeters of the dalles. There were two types of cracks noted in isolated dalles. Cracks from impact damage were of obvious origin. It is unknown, however, if more isolated hairline cracks occurred during the original curing of the concrete or are due to thermal expansion and/or the resultant stresses produced by the concrete pressing against the glass.[26] The isolated cracks generally did not destabilize the dalles in the panel matrix. These cracks appear to be an inherent condition of the material; where the glass was stable within the panel, no treatment was implemented.[27]

Laboratory Testing: Coatings for the Precast Concrete Matrix

The design team wanted to use a coating system to consolidate the friable surfaces of the panels. The design intent was to use a consolidant with a compatible water repellent, which would serve to reduce the water absorption of the panels and the surrounding concrete framework and consequently reduce the corrosion rate of the steel reinforcement in both materials. New York State environmental regulations restricting volatile organic compounds (VOC) content limited the consolidants available for use.[28] KEIM Fixativ consolidant was selected in order to conform to these restrictions. KEIM Ecotec was selected as a compatible water repellent for this product.

KEIM Fixativ contains a potassium silicate binding agent, which forms an insoluble silica gel that binds itself between aggregate particles.[29] Potassium carbonate (potash) is formed as a by-product of these reactions; it is highly water-soluble and is typically washed off by the rain. The silica gel is insoluble, however, and remains stable between the particles, serving to consolidate the friable panel surfaces.[30]

KEIM Ecotec is a solvent-free, alkyl-silicone resin with alkoxy groups.[31] According to the manufacturer, Ecotec coats porous interspaces between particles and creates a hydrophobic environment.[32] In order to develop its water repellency, Ecotec requires a higher alkaline environment than that which existed on the carbonated concrete at the Hall of Science. To elevate the surface pH of the materials at the Hall of Science, the application of Keim Fixativ was deemed an appropriate pre-treatment.[33]

Laboratory testing was performed on samples of the panels to confirm the effectiveness of the selected coatings in comparison with other common consolidation and water-repellent systems.[34] Phillips microabrasion testing found that the KEIM system substantially increased the mechanical strength of the precast concrete samples in comparison with untreated samples.[35] Water-absorption testing indicated the Fixativ followed by Ecotec also provided good water repellency and reduced the absorption by 90 percent when compared to untreated samples.[36] RILEM 11.4 water-absorption tests demonstrated that after 1,000 hours of accelerated weathering, the KEIM system still reduced the rate of absorbance of the precast concrete by approximately 66 percent.[37] The application of the KEIM treatments did not appear to affect the color of the concrete.[38]

Alkali silicate treatments generally do not penetrate below the deteriorated zone; they therefore can result in the production of a surface layer that weathers differently than underlying concrete.[39] Testing revealed that beyond the 1.5 millimeters of weathered surface, the concrete in the panels remained hard, cohesive, and dense. Therefore, only the absorbent, weathered upper zone of the concrete was expected to be affected by the KEIM Fixativ and Ecotec applications.[40] Any hardened surface formed by the application of these coatings was expected to have characteristics similar to the higher-strength concrete underneath the weathered zone.[41]

The potential for the KEIM Fixativ and the KEIM Ecotec to produce salts in the panels was assessed with conductivity tests, x-ray diffraction (XRD), and x-ray fluorescence (XRF). Four samples of the precast concrete were tested. One control sample remained untreated. The three other samples were washed with EnviroKlean Biowash, produced by ProSoCo, Inc.[42] One of the washed samples was left uncoated; one was treated with Fixativ; and one was treated with Fixativ and Ecotec.

Each sample was weighed and immersed in distilled water for 24 hours; the conductivity of the resultant solutions was measured using an ACCUMET 50 conductivity meter. The liquid obtained from this test was then filtered and evaporated, and the resultant powder was subjected to elemental analysis.

All solutions measured a low conductivity and a neutral pH, which suggests neither the biological-growth remover nor the consolidant and water-repellent treatment creates significant quantities of salts in the precast concrete.[43] Nearly one-third to one-half of the conductive material found in the treated samples was derived from the calcium sulfate hydrate (gypsum) that existed in the panels prior to treatment.[44] The Biowash contributed some chloride to the cleaned panels, and syngenite was detected in both samples treated with the Fixativ. The analysis suggested that potassium in the Fixativ reacted with the calcium sulfate hydrate (gypsum) present in the concrete and formed potassium calcium sulfate hydrate (syngenite).[45] Syngenite is a relatively unstudied evaporite that is not known to be harmful to concrete. Therefore, the executed treatment with KEIM Fixativ was not believed to bring about an added risk.[46]

Laboratory Testing: Coatings on Glass Dalles

Laboratory testing was performed to determine the effects of concrete coatings on the dalles. KEIM Fixativ and Ecotec were applied to the glass individually and in combination. Microscopic examination of the glass found that the products did not etch the blue glass but did produce a visible residue.[47] The coatings could be removed from the surfaces without leaving a chemical residue; however, the means necessary for removing the residue varied.[48]

Individually applied, the consolidant and water repellent resulted in visible depositions of product that could be removed with water and a rag. Removal of the product created by the combination of consolidant and water repellent together was more difficult. This residue could not be removed with water or solvents; a mild abrasive was required.

Tests were performed to protect the glass during coating applications by applying a temporary masking material. Such products were deemed impractical during construction, as they would require a skilled mechanic and excessive time to apply multiple coats to each dalle. Removal of the tested material left residue on adjacent concrete and in the divots and irregular surfaces of the faceted glass.

Fig. 8. Routing a crack in a panel as part of cementitious patch repair, 2010.

The final solution involved carefully wiping each piece of glass immediately after the application of the consolidant and again after the water-repellent application.[49] This procedure minimized the reaction of these products together on the glass.[50]

Field Testing: Repair of Cracks in the Precast Concrete Matrix

Repairs were necessary at through-panel cracks to reduce water infiltration into the panel and the building interior. These cracks ranged in size from approximately 0.3 to more than 1 millimeter. A variety of epoxy, lime-based, and cementitious injection materials were tested.

The epoxy-injection methods tested included Sikadur 55 SLV, Sikadur Crack Fix, and Sikadur Injection Gel. The 55 SLV and the injection gel were rejected due to their viscosities. The 55 SLV has a "super low-viscosity" and could be successfully injected into narrow cracks (0.35 millimeters and 0.4 millimeters), but significant leakage occurred at the juncture of the concrete and glass and at larger cracks, those approximately 0.7 millimeters wide.[51] Leaks occurred where the temporary crack sealer stopped adjacent to glass and at the panel edges, which were not sealed. The injection gel

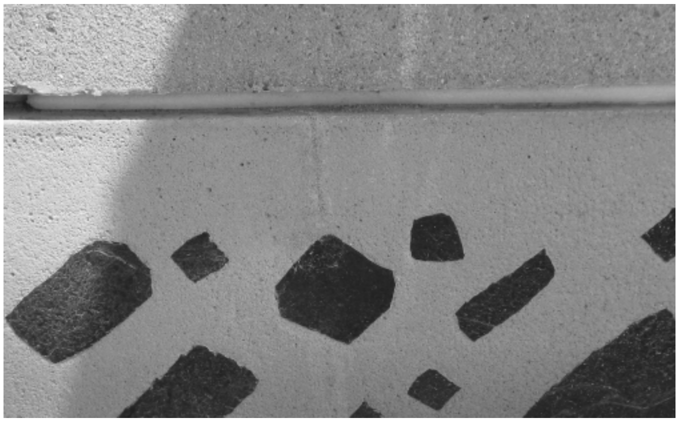

Fig. 9. Crack repair in a panel using cementitous patching material with surface-applied aggregate, 2010.

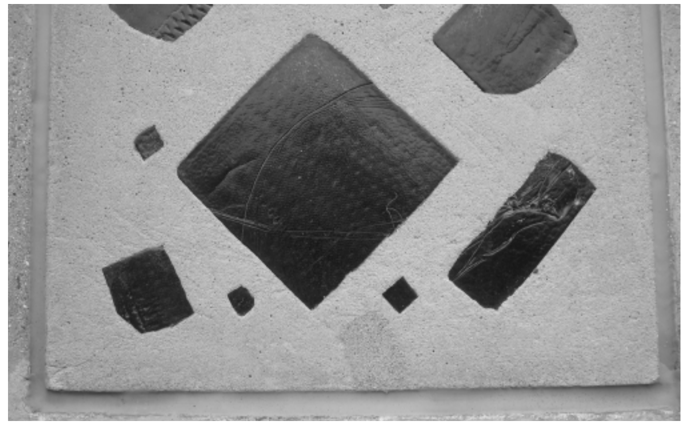

Fig. 10. The surface of a patch repair at center bottom of panel was coated with aggregate and Fixativ to further conceal the patch, 2010.

was injected into cracks 0.5 to 1.0 millimeters wide with difficulty and could not be used to fill smaller cracks.[52]

The Sikadur Crack Fix successfully filled cracks ranging in width from 0.3 to 0.5 millimeters. However, logistical problems prohibited its use. Using this material would have required sealing both sides of all cracks and the perimeter of glass dalles adjacent crack repairs; however, access to the interior face of the panels was not available during construction. Thus the contractor could not monitor the injection from the interior or clean any overflow materials from the interior face of the glass and concrete.

To evaluate possible grout-injection treatments, tests were performed using both lime-based and cementitious grouts. The materials tested included the following custom formulated and proprietary products: natural hydraulic lime (NHL, Type 5.0, strongly hydraulic); Cathedral Stone Products, Inc., Jahn M30 (Type #32) injection grout; RolPanit dispersed hydrated lime (DHL) putty; and US Heritage DHL injection mortar (DHL-IM).[53]

A variety of injection needles and syringes were used for the tests.[54] The outside diameter of each needle and syringe was used to determine the width of the crack that could be injected without drilling portals. The cracks were temporarily sealed, with openings left for injection.[55] In addition, each grout was tested as a surface-applied treatment to determine if any material successfully migrated into the open cracks through capillary action.

NHL 5.0 grout, mixed 1:1 in water, blocked all of the tested needles. The grout did flow through a plastic syringe when no needle was attached, but it frequently clogged the nozzles, proving it difficult to control. As a surface application, the material slightly penetrated the open cracks, depending on the amount of surface water present. The grout dried to a white color with no apparent cracks or shrinkage.

Jahn M30 flowed through an 18-gauge needle with minimal clogs.[56] The grout required pressure to flow through the injection apparatus and temporary dams to completely fill voids. As a surface treatment, Jahn M30 did not penetrate the open cracks through capillary action. The grout dried to a light gray color with no apparent cracks or shrinkage.

RolPanit dispersed hydrated lime (DHL) putty can be mixed to a range of consistencies using varying amounts of water. The DHL putty was mixed to a consistency capable of flowing through a 16-gauge needle, the smallest gauge tested. DHL proved moderately thixotropic in tests. However, as the volume of water was increased to lower the viscosity, the material loosened and performed with less control. The DHL penetrated open cracks when applied as a surface treatment, but cracks and shrinkage were observed in the dried material. Use of DHL would have required a pigmented, lime-based fill over the injection repairs to match the adjacent concrete surface color as the grout dried to a bright white color.

US Heritage DHL Injection Mortar (DHL-IM) is manufactured as a low-viscosity grout containing dispersing agents, which increase the workability of the material by giving it the ability to be injected through very thin openings. It is formulated to have thixotropic properties that reduce the tendency of the grout to flow uncontrollably out of open cracks. DHL-IM is used out of the packaging with no additional preparation necessary. It flowed easily through an 18-gauge needle, as well as through curved-tipped irrigation syringes, and could be injected into open cracks without temporary sealant. The grout dried to a white color with no apparent cracks or shrinkage. US Heritage DHL-IM can be pigmented; however, the manufacturer recommends filling the surface of crack repairs with a thicker DHL mortar pigmented to match adjacent surfaces.

Of the lime-based or cementitious grouts tested, US Heritage DHL-IM was the most effective for use as an injection grout to fill the surface of the open cracks in the panels at the Hall of Science. DHL-IM, when properly installed, completely filled the open cracks and did not shrink or crack when curing; this treatment therefore could appropriately waterproof the cracks. The other grouts tested performed with varying amounts of success. None of the grouts tested flowed through the open cracks and out of the back of the panels, suggesting that these injection grouts could eliminate the need for access to both sides of the panels during repairs.

Two concerns were noted with regard to grout injection. First, all of the grouts tested required either pigments or color-matched fills. Since pigments can potentially change the properties of the material, further testing would have been necessary to determine any changes in the workability of the pigmented products in the field during construction.

Additionally, testing showed that grout injection was a viable repair procedure only for cracks approximately 1.25 to 3 millimeters wide. Smaller cracks would have required drilled injection portals, which would have increased the visibility of the repairs and, similar to epoxy injections, required additional patching of the repaired surfaces. Cracks open more than 3 millimeters were wide enough to accept patching mortar and therefore did not need to be injected with epoxy or grout.

Due to the time constraints associated with the restoration and the large number of repairs to be performed, a singular approach to all cracks was desired to expedite work. Routing and filling cracks using a custom-color composite patching mortar was therefore considered, based on its known properties. Cathedral Stone Products, Inc., Jahn M90 concrete-repair mortar, already being used on site for the repair of the cast-in-place concrete, and Jahn M70 sandstone-repair mortar were tested. The Jahn M70 was eventually selected for the crack repair in the panels because it has finer aggregate than the Jahn M90 and a better working consistency for filling narrow cracks.

Repairing and Coating the Dalle de Verre

Cracks thinner than 0.75 millimeters in the panels were generally not repaired; this category included hairline separation between stable dalles and the pre-cast concrete matrix.[57] Cracks wider than 0.75 millimeters in sound exterior panels were treated with rout-and-fill repairs. Cracks were routed with custom-made, 22-millimeter diameter, 1/8-inch thick, diamond-tipped Dremel blades to a minimum depth of 3/8 inch and were then filled with the patching mortar (Fig. 8).[58] This mortar was also employed for patching holes in the panels where conduits were removed.[59] An aggregate blend was pressed into the surface of the patching mortar to match adjacent concrete colors and textures (Fig. 9).[60] This procedure was used to repair approximately 4,000 cracks.[61]

Although the original panels at the Hall of Science were cast from a prepackaged concrete mix, they exhibit a wide variation in colors. For efficiency, however, only two colors of patching mortar, a gray and a tan, were selected for the exterior panel repairs. At the surface of repairs in the bottom five levels of panels, which are at eye level, workers applied the aggregate blend and KEIM Fixativ consolidant over the patching material and adjacent concrete. This surface coating further blended the repairs (Fig. 10).

After the panel patch repairs were properly cured and the cast-in-place concrete was coated with a migrating corrosion inhibitor, the panels were coated with KEIM Fixativ and KEIM Ecotec.[62] The Fixativ was brush applied to each panel. The Ecotec was spray applied to both the cast-in-place concrete and panels.[63] Each glass dalle was wiped clean before the applied coatings dried.[64]

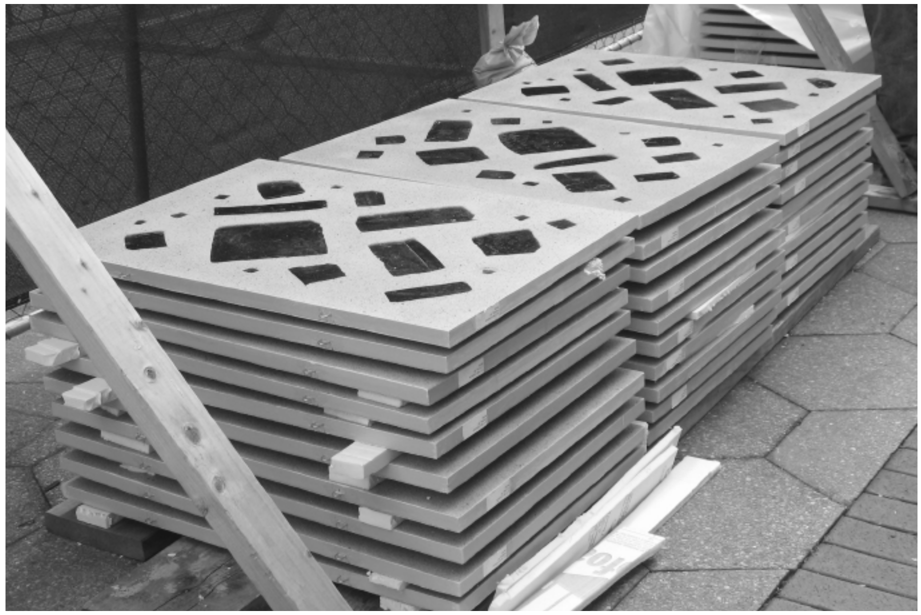

Fig. 11. New replacement dalle-de-verre panels with an epoxy matrix matching the exterior appearance of the original pre-cast concrete panels, 2009.

Replacing Severely Deteriorated Panels

After the scaffold was erected, the authors and the contractor performed a survey of the entire facade to identify repair locations. Panels exhibiting multiple wide cracks, deflection, and/or damaged or destablized glass were selected for replacement by the architect. The worst conditions were found at the parapet level of the building, where water had infiltrated behind the panels. Severe deterioration was also noted at the freestanding wall, where panels were exposed to weather on both sides.

The original manufacturer of the concrete panels, now called Willet Hauser Architectural Glass, produced new panels cast with an epoxy matrix to replace severely deteriorated panels (Fig. 11).[65] Two colors of epoxy were selected as matrix material for replacement panels. A mix of silica and mason sand was broadcast onto the surface of all the epoxy to simulate the appearance of the original concrete panels. Natural variations in the aggregate resulted in a range of tan and gray replacement panels similar to the original panels.[66]

The original glass, after careful consideration and extensive discussion with the entire project team, was not reused, due to the difficulties and expense associated with removing the dalles from the concrete panels. The new replacement panels are comprised only of blue glass, which is not faceted. The new glass has a greater light transmission, due to manufacturing limitations. While the exterior appearance of the new panels is nearly identical to the original panels, the new dalles have a different appearance when light shines through them, appropriately presenting themselves as distinct from the original. In order to eliminate any aesthetic impact caused by these variations in the glass on the experience of being within the Great Hall, original panels were moved from the freestanding wall and the non-public projection booth to the main exhibit space. The new epoxy panels were then installed at those locations and at the parapet level. By relocating the panels in this manner, only concrete panels with the original glass are visible from within the main exhibit space.

Careful consideration of replacement materials and conservation treatments based on the laboratory and on-site testing enabled the preservation of one of the most important elements of the New York Hall of Science. The current trend in concrete dalle-de-verre restoration in the United States involves replacing panels with new panels consisting of an epoxy matrix regardless of whether they originally were concrete or epoxy. By implementing alternative conservation treatments at the Hall of Science, approximately 97 percent of the original handcrafted concrete dalle-de-verre panels were retained. In 2013, as a subsequent part of the Great Hall upgrade project, the interior of the panels were cleaned, removing decades of soiling from the facets of the dalles and restoring the dramatic visual effect of this extraordinary mid-century World's Fair building.

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Notes

1. An additional example of America's interest in outer space during this time is evident in the construction of NASA's Space Park, which was the largest collection of American rockets and space vehicles assembled outside Cape Kennedy. This 2-acre park was constructed directly adjacent the Hall of Science. Warren Weaver Jr., "U.S. to Show Rockets and Space Vehicles at Fair," *New York Times*, March 9, 1964.

2. The interior enclosed space of the Great Hall is approximately 80 feet high. The Great Hall has a footprint of approximately 5,000 square feet, while the basement, which is hexagonal in plan, was designed with approximately 27,000 square feet of exhibit area. Walter Sullivan, "Hall of Science at World's Fair to Open a Month or More Late," *New York Times*, Oct. 6, 1963. The basement opened on June 16, 1964, while the Great Hall was still under construction. It served as additional exhibit space for Abbott Laboratories, the American Cancer Society, the American Chemical Society, Ames Company, Inc., the Atomic Energy Commission, the Department of Defense Office of Civil Defense, the General Aniline and Film Corporation, the Hearing Aid Industry Conference, the Interchemical Corporation, and the Upjohn Company. Walter Carlson, "3 Space Vehicles Hang in New Hall: City-Financed Fair Exhibit Rushed for Opening," *New York Times*, Aug. 30, 1964.

3. The basement was accessible by a grand staircase at the east end of the Great Hall and an elevator at the west end. A 1981 renovation included the construction of a planetarium, gift shop, and a new stair hall at the west facade of the hall. The grand staircase was removed, and the floor was filled with concrete. The reflecting pools surrounding the exterior were also removed, and new pavers were installed.

4. Models of space vehicles were hung in the Great Hall while the upper levels of the building were still under construction. They were lowered through a door in the roof while scaffolding was still erected and were suspended from cables near the ceiling. The laboratory was 30 by 12 feet in plan, and the wing-shaped taxis were 20 feet long. The exhibit was sponsored by the Martin-Marietta Company, which described the vehicles as within the capabilities of existing technology but not representative of any existing craft. They were products of the company's aerospace research program, but Gardner Displays constructed the fair models. Carlson, "3 Space Vehicles Hang in New Hall."

5. Sheldon J. Reaven, "New Frontiers: Science and Technology at the Fair," in *Remembering the Future: The New York World's Fair From 1939 to 1964*, The Queens Museum (New York: Rizzoli, 1989), 80. The show was approximately 15 minutes long and included an animated film on a 20-by-50-foot screen. Carlson, "3 Space Vehicles Hang in New Hall." The film was directed by Frank Capra, produced by the Graphic Films Corporation, and included an introduction by the television comedian Danny Thomas. Bosley Crowther, "A Disappointing Science Film," *New York Times*, Sept. 10, 1964.

6. Flora Chou, "Dalle de Verre: Modern Stained Glass," *The Challenge of Change: Dealing with the Legacy of the Modern Movement,* 10th International Docomomo Conference, ed. Dirk van den Heuvel, Maarten Mesman, Wido Quist, and Bert Lemmens (Amsterdam, The Netherlands: IOS Press, 2008), 356.

7. April Jannine Joost, "Towards the Conservation of Faceted Glass," master's thesis, Columbia University, n.d., 22.

8. Epoxy resins were more expensive than concrete. Lacey Bubnash, "Dalle de Verre / Faceted Glass: New Approaches to a Modern Material," master's thesis, Columbia University, n.d., 37.

9. Blenko Glass Company was requested to produce glass dalles in the U.S. during the late 1950s. They were "the only American firm with expertise in producing mouth blown antique glass and norman slabs." Initially, they produced various shapes of dalles, including kidney, round, angular, triangular, and star-shaped. Eventually they started to produce standard 8-inch-by-8-inch dalles that were 1 to 1½ inches thick; these are what are found at the Hall of Science. Later, 8-inch-by-12-inch dalles slightly thicker than 1 inch became the standard. John Kebrle, "The Glass," ch. 10, "Dalle de Verre," *SGAA Reference & Technical Manual: A Comprehensive Guide to Stained Glass*, 2nd ed. (Raytown, Mo.: Stained Glass Association of America, 2007), 211.

10. In order to produce the panels for the Hall of Science, Willet used 125 tons of Corson's Home-Crete. The material was selected for its uniform mix. "The Museum of Science and Technology," *Corson Flashes!, Bulletin* 13 (Aug. 3, 1964). At the time of the construction of the Hall of Science, Henry Lee Willet had produced more than 1,100 stained-glass windows around the world, including windows of Cathedral of Saint John the Divine in New York and the National Cathedral in Washington, D.C. Tania Long, "Hall of Science Studies Lighting: Daytime Effect is Sought After Dusk at Fair," *New York Times*, Oct. 7, 1964.

11. "A Modern Museum for the Space Age," *Stained Glass* (Spring 1965): 12.

12. Ibid.

13. Benes's "expertise in epoxy compounds for the stained glass profession remains unchallenged to this day." He was awarded an honorary membership in the Stained Glass Association of America in recognition of his contribu-

tion. Richard Millard, "A Personal View," ch. 10, "Dalle de Verre," *SGAA Reference & Technical Manual: A Comprehensive Guide to Stained Glass*, 227.

14. "A Modern Museum for the Space Age," 12.

15. Ibid.

16. Ibid.

17. Ada Louise Huxtable, "Romantic Hall of Science: Harrison's Building at World's Fair Reminds One of 13th Century Cathedral," *New York Times*, Sept. 10, 1964.

18. Petrographic and chemical analyses were conducted in accordance with the standard practices contained in ASTM C1324-05, *Standard Test Method for Examination and Analysis of Hardened Masonry Mortar* (West Conshohocken, Penn.: ASTM International, 2008). John J. Walsh, "Precast Panel Analysis Report," Highbridge Materials Consulting, Inc., Nov. 13, 2009, 2.

19. The quantity of fly ash estimated to be in the precast panels is considered optimal. When fly ash exceeds 25 percent cement substitution, it results in little additional pozzolanic reaction. Furthermore, the excess fly ash acts as an inert diluent and weakens the binder. Walsh, 5-6.

20. Ibid., 5.

21. Ibid., 5-6. Building Conservation Associates, Inc. (BCA), also performed carbonation testing with 1 percent phenolphthalein in 95 percent alcohol; results indicated that carbonation had begun throughout the entire depth of the concrete panel, although it is not yet complete. These findings were confirmed with a Germann Instruments Rainbow Indicator.

22. James Martin, Orion Analytical LLC, "Project 1570/80 Report," Oct. 30, 2009, 2. Thin sections of an interior and exterior panel were also produced. BCA confirmed the presence of a clear film coating as a distinct layer on the side of the interior panel that is set flush with the cast-in-place framework. Under UV light, this thin, discrete layer exhibits faint auto-fluorescence, characteristic of an organic coating. Because the samples were embedded in epoxy, the depth of penetration could not be determined. The thin section of the exterior panel clearly shows that this surface coating has eroded. No such coating could be identified on the coffer-facing sides of the panels.

23. FTIR testing of coatings on the interior and exterior cast-in-place framework did not indicate the presence of an epoxy coating, suggesting that the material was not applied to all surfaces as a final coat, as described in the 1964 article entitled "A Modern Museum for the Space Age," *Stained Glass*. Instead, two coatings, an alkyd resin and a polystyrene combined with what is likely an acrylic, were found on the exterior cast-in-place concrete framework. James Martin, Orion Analytical LLC, "Project 1589 Report," Jan. 8, 2010, 2.

24. No evidence has been found of an epoxy coating on the coffer-side of the panels.

25. Where the face of the panel had severely weathered to expose corrosion, the panel was replaced.

26. To prevent this cracking, some dalle de verre is produced with a seal, such as bitumen, around the glass, which cushions it. Vincent O'Brien, *Techniques of Stained Glass: Leaded, Faceted & Laminated Glass* (New York: Litton Educational Publishing, Inc., 1977), 36. No such cushioning material was installed around the glass in the panels produced for the Hall of Science.

27. Previous isolated interior repairs to stabilize the glass were noted later, after access was granted for the 2013-2014 interior upgrade of the Great Hall. Among these repairs was the application of sealant around isolated dalles and patching of small holes adjacent to the dalles with the rough application of cementitious material. This patching-repair material was removed, and the small holes were sealed with Sugru, a moldable silicone rubber. Sugru comes in multiple colors; blue was selected to match the color of the adjacent glass.

28. During the initial project design, Ennead Architects selected ProSoCo's Conservare OH100 followed by Sure Klean Weather Seal SL100 Water Repellent. This consolidant could no longer be used following the implementation of the VOC restrictions, which took effect in January 2005. Laboratory testing was therefore implemented to compare the KEIM and ProSoCo systems.

29. KEIM Fixativ, Safety Data Sheet (July 2001), 1.

30. Helmut Elsner and Ulrich Bethge, KEIMFarben, e-mail correspondence to Ennead Architects and BCA, (May 26, 2006).

31. KEIM Ecotec Concentrate, Safety Data Sheet (Nov. 2003), 1.

32. Both products, after their reaction, are considered highly water-vapor permeable. Helmut Elsner and Ulrich Bethge, KEIMFarben, e-mail correspondence to Ennead Architects and BCA, May 26, 2006.

33. John Bogert, KEIM Mineral Coatings of America, Inc., e-mail message to Ray Pepi, BCA, March 20, 2007.

34. The KEIM Fixativ and Ecotec system was compared to untreated concrete and the following coating systems: Sure Klean Weather Seal SL100 Water Repellent; Conservare HCT followed by Sure Klean Weather Seal SL100 Water Repellent; and Conservare OH100 followed by Sure Klean Weather Seal SL100 Water Repellent.

35. The KEIM system reduced the average grams of material lost during testing. Compared with the other systems tested, only the Conservare OH100 followed by the Sure Klean Weather Seal SL100 Water Repellent performed better. AMT Laboratories, "New York Hall of Science, Queens, NY Laboratory Report, Project No. 0604-04," May 2006, 7. Phillips microabrasion testing is based on ASTM 418 Abrasion Resistance of Concrete by Sandblasting. "Laboratory Testing," AMT Laboratories, http://www.amt-labs.com/services_testing_special.aspx (accessed Feb. 20, 2010).

36. AMT Laboratories, "New York Hall of Science, Project No. 0604-04," 4.

37. AMT Laboratories, "New York Hall of Science, Queens, NY Laboratory Report, Project No. 0701-08," April 2007, 4-5.

38. AMT Laboratories, "New York Hall of Science, Project No. 0604-04," 6.

39. Ibid., 9.

40. Thin sections were produced of coated concrete samples removed from the Hall of Science in order to determine the depth of penetration of the coatings. The findings of this analysis were inconclusive.

41. KEIMFarben, e-mail correspondence to Ennead Architects and BCA, May 26, 2006.

42. EnviroKlean Biowash was a biocide used to remove light biological growth. The samples did not exhibit biological growth, but Ennead Architects had selected this product as a cleaner for the restoration due to the visible presence of biological growth on the building.

43. The sample treated with the biological-growth remover, consolidant, and water repellent weighed 842 grams and yielded a conductivity of 732 microSiemens per centimeter. The sample treated with the biological-growth remover and consolidant weighed 847 grams and yielded a conductivity of 781 microSiemens per centimeter. The sample washed only with the biological-growth remover weighed 808 grams and yielded a conductivity of 1040 microSiemens per centimeter. The untreated sample yielded a conductivity of 332 microSiemens per centimeter.

44. The calcium sulfate hydrate (gypsum) was detected through x-ray diffraction (XRD) performed on an untreated sample of concrete. X-ray fluorescence (XRF) testing detected mostly calcium and sulfur with smaller amounts of silicon, chlorine, and potassium.

45. XRF indicated the concentration of potassium in the sample treated with Ecotec and Fixativ was 21.9 percent and the concentration in the sample treated with only Fixativ was 31.0 percent. The sample that was washed only with Biowash had a potassium concentration of 5.79 percent.

46. Although the preference would have been to rinse the panels after Fixativ application to remove this salt, the manufacturer's recommendations for product application prohibited it.

47. The products were tested only on the cobalt blue glass surfaces. The red, green, and yellow dalles at the building were not available for testing. Because all of the glass dalles at the Hall of Science are embedded in concrete (a high pH environment) and do not appear to exhibit etching, the repair strategy was designed with the assumption that all of the colors of dalles at the Hall of Science are resistant to etching by high pH materials, such as the concrete coatings proposed for the restoration.

48. The migrating corrosion inhibitor selected for application to the cast-in-place concrete framework at the Hall of Science was also applied to the glass during testing, both alone and in combination with the consolidant and water repellent. This product was not specified for application to the dalle-de-verre panels, its effect on the glass was reviewed as a precaution. The migrating corrosion inhibitor did not etch the glass. It formed a thick white film, which could be removed using water and a rag.

49. The panels were protected during application of the migrating corrosion inhibitor, and the building was thoroughly rinsed after application of this material. This procedure eliminated concern regarding residue on the glass from this product.

50. This procedure was approved by the coatings manufacturer, who preferred wiping the glass to applying protection, since it allowed the water repellent to penetrate the concrete at the perimeter of the glass.

51. Sika Corp., "Products by Name," http://www.sikaconstruction.com/con-prod-name.htm#con-prod-Sikadur55SLVNEW (accessed Feb. 24, 2010).

52. The temporary crack sealer used for the epoxy-injection tests was StripSeal, produced by ChemCo Systems; this material could not contain the injection gel under the pressure of the hand-pump grease gun used for testing.

53. Open cracks were cleaned and prepared using a variety of solutions, including Surfonic JX-80 (1 percent aqueous solution), acetone, denatured alcohol, and water. All of the solutions tested worked well to irrigate and to flush dust from the open cracks.

54. Hypodermic needles (20, 18, and 16 gauge), flat-tipped injection tubes (18 gauge), 12cc curved-tip dental irrigation syringes, and plastic syringes were tested.

55. Non-oil-bearing clay and hot-melt glue were used as temporary sealants. The clay dam obscured the visibility of the injection treatments, and the results were varied when the dam was removed. The hot-melt glue provided some transparency. Both temporary sealers could be removed easily without damaging the surface of the panel.

56. Jahn M30 was mixed according to the manufacturer's specifications. Type #32 was used for this testing.

57. Cracks greater than 0.5 millimeters were repaired at the parapet level of the building due to increased exposure and weathering of this area.

58. The blades were specially produced for this project by Wagner Precision Rotary Instruments, LLC.

59. At these locations, a galvanized screen coated with a rust-inhibitive coating was installed at a rabbet for reinforcement.

60. Willet Hauser Architectural Glass supplied the sand mix applied to the panels; it was the same aggregate as that is being used on the surface of new epoxy replacement panels.

61. This repair quantity was estimated by Denio Sturzeneker, foreman for Structural Preservation Systems, in a conversation with Laura Buchner, BCA, Oct. 30, 2009.

62. Based on the condition of the panels, KEIM recommended the Fixativ be applied at the Hall of Science in one application of 2 parts Fixativ to 1 part water rather than the two applications of 1:1, which is standard. Applying this material once reduced the amount of glass protection required. The water repellent was mixed 1 part Ecotec to 9 parts water and was applied after the Fixativ had cured for 72 hours, per manufacturer's recommendations.

63. New silicone sealant was installed around all exterior dalle-de-verre panels prior to the application of the water repellent.

64. At isolated locations, these materials were not sufficiently wiped, and they reacted to form a white residue on the glass. The contractor gently removed this residue with 3M Scotch Brite Pads, type Light Duty White, and the glass was rinsed with water. This process was found to remove the material without visibly scratching the glass.

65. While dalle de verre is still commonly produced with a concrete matrix elsewhere in the world, the industry standard in the United States is to produce panels with an epoxy matrix.

66. The coffered side of the epoxy panels is coated with sand and therefore does not match the uneven, white surface of the original concrete panels. This surface is not visible in public areas.

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