INVESTIGATION OF STAINING OF HARD-SET SANDSTONE MASONRY PAVERS

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ABSTRACT
Sandstone pavers were installed in a hard-set application outside a school building in the northeastern United States in early 2010. Soon after installation, brown staining was observed on the pavers, particularly in areas where the stone was either directly exposed to water or where runoff flowed over the surface of the stone. Several methods of stain removal, including power washing and the application of a proprietary ferrous cleaner, were attempted with varying degrees of success. In early 2011, crystalline efflorescence was noted on the surface of the stone in addition to the staining.

A testing regimen was developed by the authors to determine the cause of the staining and evaluate installation methods with the goal of reducing the tendency for future staining after paver replacement. Samples of both the installed stone and previously uninstalled samples were sent to an independent laboratory for analysis of the stain and deposit constituents. In addition, efflorescence testing was performed on several mock-ups in the laboratory. The mock-ups used various installation methods and materials, including the materials and mix design used in the original paver installation.

The test results indicated that the staining was organic, formed by dissolution of naturally occurring trace organic materials in the stone. These materials were released as alkalinity increased due to soluble salts migration. The efflorescence was the result of the naturally occurring soluble salts present in the cementitious mortar joints and setting bed of the paver system. Recommendations to mitigate the staining and efflorescence in future installations were developed.

KEYWORDS: efflorescence, mortar, paver, sandstone, staining, testing

INTRODUCTION
Shortly after the installation of sandstone pavers and stair treads in a hard-set application at the entrances to a school building in the northeastern United States in early 2010, brown staining was observed on many of the stone surfaces. In general, the observed staining appeared heaviest in locations where the stone was subject to water runoff over the surface of the stone pavers or exposed directly to water. Although several methods of stain removal, including power washing and the application of a proprietary ferrous cleaner, were attempted by the subcontractor

responsible for the paver installation, none of the cleaning methods was successful in permanently removing the staining.

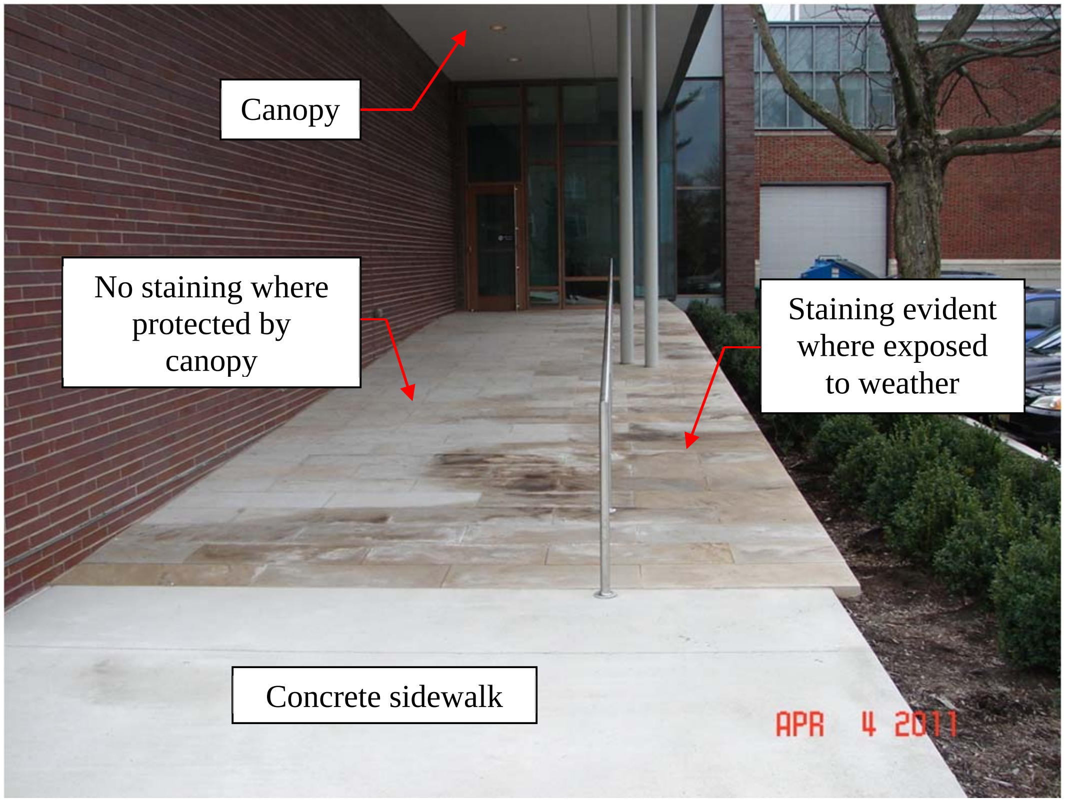

Figure 1: Staining not observed where pavers were protected from weather by canopy

According to the facility maintenance staff, de-icing chemicals were applied to the surface of the stone entrances and stairs over the course of the winter as a snow and ice removal method. Reportedly, several different de-icing chemicals may have been employed including sodium chloride (rock salt) and proprietary ice melt materials containing sodium, potassium and magnesium salts, urea (NH_2-CO-NH_2), and undisclosed additives that likely contained phosphates and nitrates.

In early 2011, crystalline efflorescence was noted on the surface of the stone in addition to the brown staining. Both the stains and the efflorescence tended to be most severe at locations exposed to a high volume of water, such as along the edges of canopies and at low spots where water could collect. As a result, at the request of the Owner, the pavers were removed and replaced during the summer of 2011.

MATERIALS TESTING

A testing regimen was developed by the authors to determine the cause(s) of the staining and efflorescence as well as evaluate various installation methods with the goal of reducing the tendency for future staining. Samples of both installed and previously uninstalled pavers were sent to an independent laboratory for analysis and testing. In addition, efflorescence testing was performed on several mock-ups of installed pavers in the laboratory. The mock-ups used various installation methods and materials, including the materials and mix design used in the original paver installation.

The independent laboratory performed the following tests:

- Efflorescence testing on paver samples in general accordance with the procedure of ASTM C67, "Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile;"

- Ion chromatography on previously installed and uninstalled pavers, setting bed, and mortar joint samples;

- Leaching-Inductively Coupled Plasma (ICP) Spectroscopy on stained and unstained pavers;

- Semi-Quantitative X-Ray Fluorescence (XRF) (Oxidized Basis) on stained and unstained areas on the same paver sample; and

- Loss on Ignition on stained and unstained areas on the same paver sample.

Efflorescence testing was performed on samples of stone removed from the original installation as well as samples of previously uninstalled pavers ("attic stock"). Of the five previously installed samples tested, four experienced brown staining after seven days of testing (Figure 2). Subsequent testing on attic stock which had never been placed into service did not result in staining over the same period of time.

Figure 2: Four out of five previously installed paver samples effloresced

High contents of soluble sodium, potassium, calcium, and sulphate were found in both the setting bed and mortar joint samples from the original installation by ion chromatography. In addition, high levels of soluble chloride were noted in the mortar joint samples. These elevated contents in the setting and joint materials were reflected in the previously installed paver sample testing results. By contrast, much lower levels of these materials were observed in the attic stock. A significant phosphate concentration was obtained from the previously installed paver samples only. These results (Table 1) indicated that the installed paver was exposed to soluble salts from the setting bed, mortar joints, and applied de-icing chemicals, and that the natural permeability of the stone allowed for significant transport of these materials through the stone to the surface of the pavers.

Table 1: Results of Ion Chromatography Testing

Ion	Concentration (ppm)			
	Previously Installed Paver	Attic Stock Paver	Setting Bed	Mortar Joints
Sodium	160	2.0	404	965
Potassium	437	4.3	1187	3512
Calcium	51.0	28.6	2850	2020
Sulphate	83.2	4.1	133	259
Chloride	17.6	4.6	19.1	155
Phosphate	31.4	0	0	0

The results of the ICP spectroscopy testing (Table 2) were in general agreement with those obtained by the ion chromatography testing. Elevated levels of potassium, sodium, sulphur, and phosphorus were observed in the stained sample relative to the unstained attic stock sample.

Table 2: Results of ICP Spectroscopy Testing

Ion	Concentration (ppm)	
	Previously Installed Paver	Attic Stock Paver
Sodium	1163	11.5
Potassium	>2482	6.8
Sulphur	174	4.4
Phosphorus	84.3	0.4

Semi-quantitative XRF performed on stained and unstained areas of a stained paver sample found high levels of Na_2O, K_2O, CaO, and S within the stained areas; these results (

Table 3) were also in agreement with the previous test results. Levels of iron and manganese were not found to be elevated within the stained areas relative to the unstained areas, indicating that the stains were not the result of ferrous or other metallic compounds.

Table 3: Results of Semi-Quantitative XRF Testing

Compound	Concentration (%)	
	Stained Area	Unstained Area
Na_2O	44.3	<0.5
K_2O	8.52	0.07
CaO	7.27	0.23
S	0.80	<0.05
Fe_2O_3	0.22	0.27
MnO	0.03	0.03

Loss on ignition testing was performed to determine if the staining was organic in nature. Heating to 1000°C results in the removal of most organic stains. Because the staining was removed by heating, it was confirmed that the staining was organic and not the result of soluble metals.

The test results and a review of the literature led to the conclusion that this particular sandstone was susceptible to organic staining as a result of a reaction between the stone and alkalis. Although this phenomenon is more well-known and documented in limestone, it can occur in sandstone as well. An article by Hartog and McKenzie [1] briefly quoted the Building Materials Evaluation Handbook as stating that exposure to portland cement "will always stain limestone, marble, and some sandstones." After the staining of these pavers was observed, a representative of the quarry that supplied the stone stated that the staining was a known issue with this particular sandstone and resulted from contact between the stone and the mortar in the presence of water. Therefore, these sandstone pavers will always react with alkalis in cement, resulting in some amount of brown staining. Any installation that requires this particular sandstone to be in contact with a cementitious material in a moist environment will cause the brown staining to occur.

Similarly, because of the porous nature of the sandstone, there is a potential for soluble salts, either from de-icing chemicals or from the cementitious setting materials, to be deposited on the surface of the stone in wet service conditions. The severity and permanence of this efflorescence would depend on the specific salt deposits.

Based on the results of the independent laboratory testing described above, and the conclusions drawn from that testing, the authors developed an experimental mock-up program with samples fabricated in accordance with the matrix presented in Table 4. This program was created to develop recommendations for setting sandstone pavers or other porous stones that are susceptible to alkali staining and efflorescence formation. According to the installer, the original stone pavers were set in a very stiff mortar ("dry pack") setting bed, commonly utilized to set heavy pavers and stair treads. The dry pack material used for the testing was mixed in accordance with the proportions used in the original installation and to a consistency of wet sand. Both the dry pack and typical Type M portland cement-lime mortar samples were mixed using the same materials used in the original paver installation. All samples, with the exception of the ASTM C33 sand sample, used the same fine aggregate used in the original paver installation. All mock-up samples had a waterproof material applied to their vertical surfaces to prevent evaporative losses from the sides and were set in direct contact with water under laboratory conditions. The sample configuration ensured that all water absorbed by the base of the specimen evaporated from the top surface, consistent with the actual construction in-place. A cementitious slurry comprised of a latex additive and white cement was applied to two samples prior to their installation in the setting bed and mortar to reduce the permeability of the stone where it was in contact with mortar.

Table 4: Mock-Up Testing Matrix

Specimen	Setting Bed and Joint Material	Number of Pavers		Application of Latex-Modified Slurry
		Previously Installed	Attic Stock	
A	Dry pack	3	3	No
B	ASTM C33 sand	3	3	No
C	Type M mortar (gray cement)	3	3	No
D	Type M mortar (white cement)	0	1	Yes
E	Latex-modified Type M mortar (white cement)	0	1	Yes

After approximately two days of exposure, the dry-pack mock-up (Specimen A) began to evidence a crystalline efflorescence deposit on both the previously installed and attic stock pavers. After one week, all of the pavers in Specimen A were also experiencing significant brown staining (Figure 3). Similar staining was observed after one week's exposure on all of the pavers of the mock-up created with the gray Type M cement (Specimen C) and the previously installed pavers in the flexible pavement mock-up (Specimen B). Interestingly, no staining was evident on the attic stock pavers in Specimen B even after six weeks of exposure (Figure 4), indicating that the formation of brown stains on the sandstone was related to its exposure to cement.

Figure 3: Brown staining on all pavers of Specimen A (approximately one week exposure)

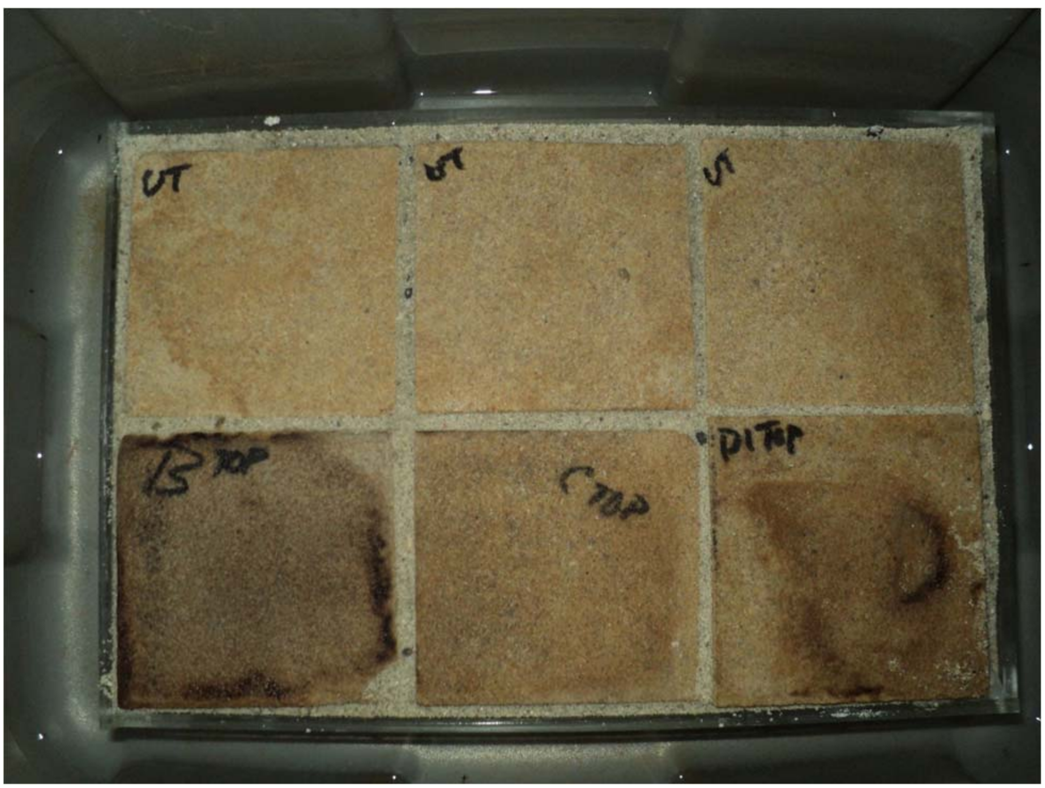

Figure 4: No staining on attic stock pavers (top row) of Specimen B (approximately six weeks exposure)

Little to no brown staining was observed on the white Type M cement mock-up (Specimen D) and the latex-modified mortar mock-up (Specimen E) after approximately four weeks of exposure. In addition, the top surfaces of these specimens appeared less saturated than those of the other mock-ups. The application of the latex-modified slurry to the paver surfaces appeared to retard the flow of water through the paver, delaying the formation and reducing the severity of staining.

CONCLUSIONS

Based on the results of the testing, the following conclusions were reached regarding the efflorescence and staining observed on the installed pavers:

- The brown staining occurred only in pavers in contact with cementitious materials in the presence of water; paver samples from the attic stock set in sand and exposed to water did not exhibit staining. Therefore, the staining is the result of an interaction between the stone and the alkaline cementitious materials in the setting bed.

- The brown staining was organic in nature and not the result of oxidation of metallic compounds in the stone.

- Use of latex-modified cementitious slurry on the pavers significantly reduced the volume of water passing through the setting bed and into the stone and subsequently reduced the severity of the staining. However, this did not entirely eliminate the staining. It only reduced the severity and minimized the rate of progression of the staining.

- The observed patterns of staining on the installed pavers indicated that the degree of exposure to water and runoff had an effect on the severity of staining. Areas where water was in constant direct contact with the masonry exhibited the most significant staining.

- Other forms of efflorescence were likely the result of dissolved salts transported through the porous stone and dry pack matrix. Some of these salts occur naturally within a cementitious material; other salts were added as the result of the application of de-icing chemicals.

RECOMMENDATIONS

In applications where brown staining is considered unacceptable, even temporarily, it is recommended that porous sandstones or limestones not be utilized in an exterior hard-set paver application; it can be used either indoors or for flexible pavements where the paver is set in inert sand material. If some amount of staining is considered acceptable, the following installation and maintenance recommendations may reduce the tendency or severity of the stone paver staining:

- Ensure proper slope for drainage on both the surface of the pavers and the waterproofed concrete base. Variations in the thickness of the setting bed can be used to slope the surface of the stone pavers.

- Use low-alkali cement for the setting bed and pointing mortar as recommended in the Indiana Limestone Handbook [2].

- Use a Type M portland cement-lime mortar for the setting bed as recommended in Brick Industry Association (BIA) Technical Notes 14C [3] and 29 [4]. A latex admixture may be added to the mortar in accordance with the manufacturer's instructions to reduce the overall permeability as recommended by BIA Technical Note 14C [3] for extreme environments. Place the mortar with a block mortar consistency and screed to the appropriate level. Allow the mortar to set to a consistency sufficient to support the pavers prior to the application of significant load.

- Provide a layer of cementitious damp proofing (either a proprietary product or a thin coat of latex-modified neat cement slurry) to the back side and the surfaces of the mortar joints as recommended by the Indiana Limestone Handbook [2].

- Use a Type N portland cement-lime mortar in the mortar joints between pavers as recommended in the Indiana Limestone Handbook [2].

- Do not clean the stone pavers with alkaline or acidic cleaners as either will exacerbate the formation of the staining. Use mild detergents and/or power wash with clean water only to clean the pavers.

If the sandstone is used for pavers in a hard-set application, the resulting staining should fade with time and exposure to weather regardless of the implementation of the above recommendations.

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