"TROUBLE UNDER FOOT"
RESURFACING HISTORIC FLOOR SYSTEMS

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ABSTRACT

At several school buildings in New York City, initial efforts to replace the tile wearing surfaces on clay tile arch floor systems were fraught with difficulties. Many of the replacement floors began to crack and heave within a few months after installation. The authors conducted in-situ and laboratory studies of the flooring systems, and identified numerous causes that contributed to the failures. These studies included a detailed comparative laboratory study of five cementitious leveling compounds that had been used in floor resurfacing projects.

Key words: Clay Tile Arch, Cinder Concrete, Flooring, Cementitious Self-Leveling Underlayment

1 INTRODUCTION

New York City is home to the largest public school system in the United States, with more than 1,200 buildings serving over one million students. These buildings form a rich practical workshop representing construction technology from four centuries, dating from the eighteenth century and continuing into the twenty-first century. The majority of the buildings investigated, however, span from the late nineteenth through the mid-twentieth century.

Over a five-year period the authors investigated building performance problems at dozens of schools throughout the city. In broad terms, the wide variety of issues we investigated almost always involved those elements of the building most subject to wear: the exterior envelope and the interior floors. This paper focuses on challenges related to resurfacing complex historic floor systems.

Clay tile arch floor slab construction was commonly used in the early decades of twentieth century. This was an especially active period of school construction in New York City, and hundreds of these floors remain in service. Widely used before the advent of contemporary reinforced concrete slabs, clay tile arch construction proved to be an effective and durable structural system. However, these historic floors have several unique characteristics that need to be understood when planning and executing a resurfacing program. Without a proper understanding of the substrate, resurfacing work is likely to damage the underlying floor system and compromise the integrity and stability of the new floor finish.

This paper provides an overview of clay tile arch floor slab construction, with particular attention to characteristics of this type of construction that require consideration when designing a resurfacing program. The findings of our field and laboratory studies are presented, including a detailed review of a comparative study of five cementitious self-leveling underlayment materials performed as part of our work.

2 BACKGROUND

The New York City School Construction Authority is currently engaged in a long-term program to replace aging floor systems at hundreds of school buildings throughout the city. In most cases, vinyl asbestos tile is abated and replaced by vinyl composition tile. In many cases significant substrate preparation is required, especially at older buildings, which often have complex and fragile floor systems. Many of the older school buildings evaluated have clay-tile arch floor slab construction, topped with cinder concrete fill and a thin concrete topping.

At several school buildings, initial efforts to replace the tile wearing surfaces on clay tile arch floor systems were fraught with difficulties. Many of the replacement floors began to crack and heave within a few months after installation. The authors conducted investigations of these failures at seven of the affected schools, including both a field investigation and laboratory studies of extracted core samples.

The field and laboratory studies revealed several issues related to the resurfacing materials that warranted further investigation. To evaluate these issues more thoroughly our client commissioned a comparative laboratory study of five cementitious self-leveling underlayment materials that had been used in floor resurfacing projects. Evaluation of mixing, placement, and curing characteristics of the compounds was conducted; and laboratory testing of samples extracted from the mixes was also performed.

3 CLAY TILE ARCH CONSTRUCTION

Hollow clay tile arch floor systems date from the late 1800s and were in use as late as the 1930s. They consist mainly of hollow clay tile units spanning between steel beams, and topped with a leveling course and finish flooring. These slabs are mainly one-way spans; each arch spans between steel or iron beams. Hollow clay arches were used as structural supports and were typically topped with cinder concrete or other cementitious topping to provide a level surface. In many cases, wood was also used as a topping material. There are two basic types of clay tile arches: flat arch and segmental arch. Both types of arches share similar structural properties; however, the segmental arch provided higher strength and greater economy.

The flat arch flooring system resembles the well-known jack arch, in which segmented tiles interlock to carry load. The thickness of these arches ranges from 6 to 15 inches. Typical spans range from 4 to 7 feet. Figure 1 shows the typical construction of a flat arch.

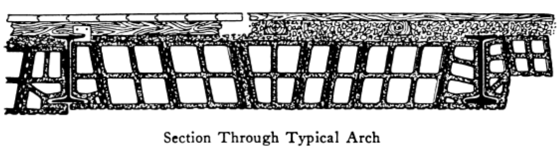

Figure 1 - Flat arch (Stecich and Stockbridge)

The skew (end) tile "embraces" the framing beams, providing fireproofing protection at the same time. If the skews are too short to fully cover the beam surface, soffit tile units 2 inches thick are locked in between the skews to cover the bottom flange of the beam. The inter tiles fill the span of the slab; their ends are slopped to help lock themselves in place. The key, or keystone, locks the entire arch together, thus providing its stability. As with any arch, flat arches exhibit thrust from developing compression. To help counteract this effect, tie rods, usually 3/4 inches in diameter or so, are connected to the beam webs, and are located at about 3 inches from the bottom surface of the arch. These rods are usually spaced between 3 and 15 feet, depending on the length of the span and the total floor load. Some middle span arches, however, do not need tie rods because adjacent arches provide thrust resistance.

The segmented arch more closely resembles a true arch. The elements of the segmented arch are similar to those of the flat arch. Unlike the flat arch, however, tile thicknesses can be between 6 and 8 inches, and the arches can achieve greater spans, some at 15 feet between the beams. Segmental arches can rise from 3/4 to 2 inches per foot. The arches are filled with cinder or stone concrete, and serve as a substrate for the top layer or surface finish. The concrete fill also provides additional strength to the floor to resist the imposed loading. This added strength is also manifested by the composite action provided by the combination of the clay tile, the concrete, and the beam, the same as the flat arch. Topping of the slab has traditionally been cinder fill, cementitious fill, and wood blocking. Figure 2 shows the typical construction of a segmented arch.

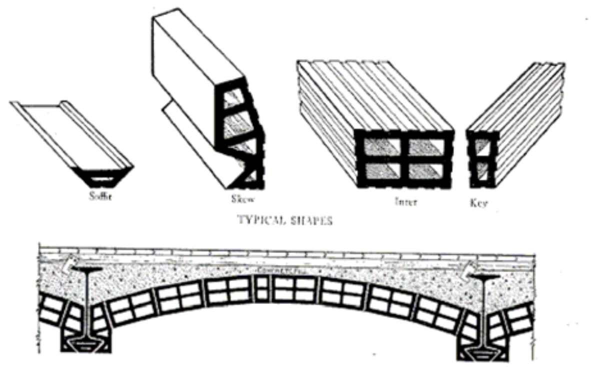

Figure 2 - Segmented arch and components (Plummer and Wanner)

Clay tile arches are typically stronger and stiffer than modern floor slabs designed for the same applications. If strength verification of a clay tile arch floor slab is required, load testing should be considered. The authors have conducted load testing to confirm that floor systems of this type are generally very conservatively designed.

4 SUMMARY OF INITIAL INVESTIGATIONS

In 2002, we investigated early failures of recently replaced flooring systems in seven New York City schools constructed between 1890 and 1941. As part of our investigation, several core samples were extracted from each of the floors and evaluated via petrographic and chemical laboratory techniques. Three categories of contributing factors were identified: (1) historic floor slab vulnerabilities, (2) the workmanship of the flooring contractors, and (3) properties of the new materials used to resurface the floor.

4.1 Historic Floor Slab Vulnerabilities

Inspection openings and core samples revealed that the underlying floor system was often severely cracked and frequently displaced. It appeared that the leveling underlayments had been used to conceal this damage. Based on the cracking and heaving of the finished floor that occurred shortly after installation, it is likely that the upper cementitious layer of the historic floor system was shattered and loose when the leveling material and new flooring was installed.

4.2 Workmanship

Custodial staff who had observed the resurfacing work reported that the slabs were typically prepared via shot blasting. The thin cementitious topping that typically forms the upper layer of clay tile arch systems may appear to be a solid concrete slab, but it is far more vulnerable to impact damage from heavy scraping, shot blasting, and other aggressive techniques to remove old finish flooring and prepare the substrate for installation of new flooring.

Inspection openings and core sample extraction also revealed multiple layers of leveling material and widely varying application thickness; applications as thick as 3 inches were observed. Most manufacturers recommend a maximum thickness of 1/2 inch. Petrographic and chemical analysis revealed aggregate settlement and soft cement paste, both indicative of excess mix water.

4.3 Properties of New Materials

Chemical analysis revealed that the leveling materials generally contained added gypsum, rendering them vulnerable to moisture. Also, with the exception of the surface preparation techniques, the workmanship issues identified were predominantly related to the leveling materials. In order to better understand these materials and evaluate whether they may be appropriate if properly installed, we conducted the testing described in the following section.

5 OVERVIEW OF MATERIALS TESTING

Detailed laboratory studies were conducted to evaluate the properties and performance of five proprietary floor leveling mortar products. Several bags of each product were purchased and installed on small concrete slabs specially cast and cured for these studies. The slabs were designed to represent a sound and properly prepared floor substrate. Two samples of each product were prepared: one in strict accordance with the manufacturer's recommendations, and one with moderately more than the recommended amount of water. Studies of core samples from leveling mortar installations indicated that over watering might be a common practice. Qualitative observations of the materials were recorded during mixing, placement, and curing. Drying shrinkage was also measured on cast prisms of self-leveling mortar, and moisture vapor emission tests were conducted starting 24 hours after each sample placement. Petrographic and chemical studies were performed on both the dry powder and cured specimens for each product. Also, the slabs were examined for cracking periodically for about 3 months after placement.

5.1 Overview of Products Evaluated

All of the self-leveling mortars we studied were portland cement-based products with a fine aggregate. Each product also included a proprietary blend of admixtures to control its properties. When mixed with water, they develop a consistency akin to American pancake batter, and are poured onto the prepared substrate. Light troweling during placement may be necessary to spread the material, but gravity does most of the work of leveling the product, and no finish troweling is recommended or desirable. Manufacturers' literature for each of the products we evaluated states that their product cures and dries quickly, and that the mortar will be sufficiently hard and have a moisture vapor emission rate sufficiently low for a finish floor to be placed after no more than 24 hours.

Drying shrinkage of portland cement matrices is an issue that affects all cementitious concrete materials. Several inherent characteristics of leveling mortars make them especially vulnerable to drying shrinkage; these include the typical thinness of installation, lack of wet curing (wet curing is not required by the manufacturers of the tested products), low aggregate content, and lack of fiber or metal reinforcement. The leveling mortars we studied employ a variety of mechanisms to control drying shrinkage, principally including a strong substrate bond and the inclusion of gypsum or a related sulfate compound in the mix. Both of these mechanisms are potentially problematic; gypsum can cause continued expansive formation of ettringite in the presence of moisture, and the substrate bond is highly dependent upon proper execution of all aspects of the installation. Previous studies also showed that aggregate segregation and associated differential shrinkage are significant factors that adversely affect leveling mortar performance. In many cases petrography revealed that aggregate particles had settled to the bottom of the leveling mortar layer, leading to cracking, differential shrinkage across the thickness of the mortar, and upward curling. Figure 3 schematically illustrates the curling phenomenon. Figure 4 shows the effects of this phenomenon at one of the facilities we studied.

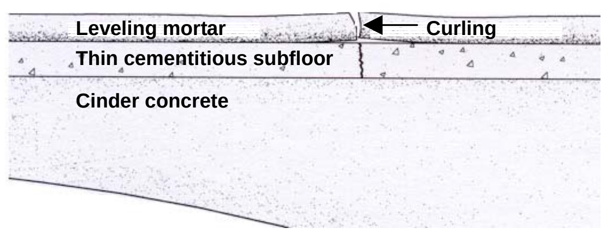

Figure 3 - Curling of leveling mortar (schematic)

Figure 4 - Cracking and curling of leveling mortar (Beasley)

5.2 Substrate Design and Preparation

Twelve concrete slabs were cast and cured to provide good substrate conditions for the leveling mortars (see Figure 5). Each slab measured 4 feet square by 4 inches thick. The slabs were cast with plain (unreinforced) 4,000 psi concrete. A notch was tooled into each slab to create an abrupt thickness change in the leveling mortar. The notch was 1/2 inch wide by 1/2 inch deep, inset 12 inches from one edge of the slab, and extended the full width of the slab. The slabs were cast and allowed to cure for approximately 6 weeks, including an initial 7-day wet cure.

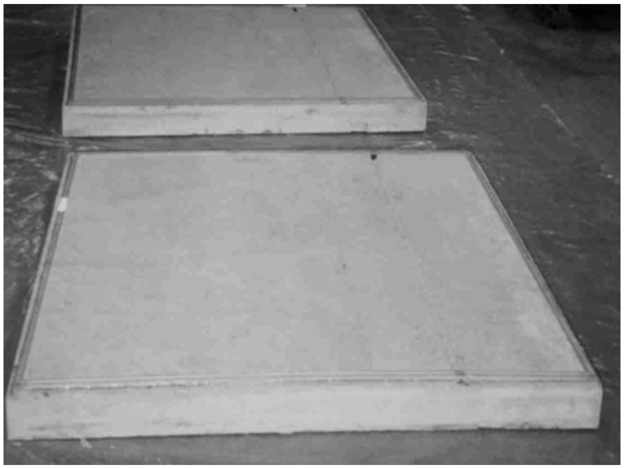

Figure 5 - Concrete slabs cast for laboratory studies

Four weeks after being cast, the slabs were shot blasted to remove laitance and create a rough surface to improve bond characteristics. After shot blasting, a polycarbonate lip with a square cross section approximately 13 mm high was installed around the perimeter of each slab to control the placement and depth of the leveling underlayments.

5.3 Mixing and Placement

Several bags of each leveling underlayment were purchased, as well as a container of the liquid primer for each product (the manufacturer of every tested product also produced a proprietary primer).

The leveling mortars were installed on the sample slabs approximately 6 weeks after the slabs were cast. During mixing and placement we qualitatively evaluated the ease of installation or "user-friendliness" of each product.

Concrete slabs were prepared using each primer, following the manufacturer's recommendations regarding dilution and drying time before application of the leveling mortar.

Each leveling mortar was mixed in carefully measured half-bag quantities. The half-bag quantities were measured based on the actual weight of each bag and equally distributed into two similar containers of equal weight. A drill and paddle mixer at 500 RPM was used for mixing. The mixing water was placed in a clean 5-gallon plastic bucket, and the dry product was added with a concrete scoop while mixing continuously.

After mixing, the material was poured onto the prepared substrate and lightly troweled to spread it uniformly. A small amount of the freshly mixed material was drawn off during the placement to prepare test bars for drying shrinkage evaluation. Placement is shown in Figure 6.

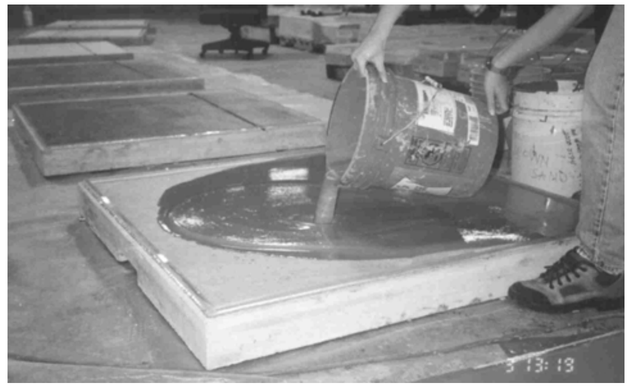

Figure 6 - Placement of leveling mortar

5.4 Monitoring and Testing

After placement, the completed leveling mortar sample installations were evaluated via a series of mechanical tests, petrographic examinations, and chemical analyses. Periodic observations continued for a period of approximately 3 months, primarily to monitor crack formation and growth.

5.4.1 Final Set

Four of the five manufacturers provide a final set time in their product literature. Measurement of final set time was based on ASTM C191, *Time of Setting of Hydraulic Cement by Vicat needle*. For the properly mixed materials (without excess water) set times ranged from 1.83 hours to 3.50 hours. The product literature for the tested products provided final set times that range from 2 to 4 hours. Of the properly mixed products, only one did not comply with the stated set time (stated final set time was 2.5 hours, measured final set time was 3.5 hours).

5.4.2 Moisture Vapor Emission Rate

Moisture vapor emission rate (MVER) tests were performed based on ASTM F1869. Each manufacturer's literature claims that finish flooring can be installed over the leveling mortar after a specified period of time, ranging from 12 to 24 hours. Industry standards for vinyl composition tile typically specify that the MVER of a cementitious substrate should not exceed 3 lbs./1000 sq. ft./24 hours (3 lbs.), hereinafter referred to as 3 lbs. Each test was started approximately 24 hours after the leveling mortar was placed, based on the longest minimum curing time recommended by any of the manufacturers (prior to tile installation). In addition to the leveling mortar MVER tests, a control test was run concurrently on one of the extra slabs. This test yielded a MVER of 4.39 lbs.

5.4.3 Drying Shrinkage

Drying shrinkage was measured based on ASTM C157, *Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. Four prisms, each 1 inch square by 11-1/4 inches long, were cast from each leveling mortar batch, for a total of 40 prisms. Each prism was cast with embedded steel contact points to facilitate precise length measurements. These samples were measured periodically over the 28 days following casting, and length changes were recorded and used to calculate drying shrinkage. With the exception of one product, which actually expanded by more than 0.50%, all products experienced various degrees of drying shrinkage, ranging from a high value of 0.57% expansion to a low value of 0.0077% shrinkage.

5.4.4 Cracking

The sample installations were monitored periodically for cracking, with the final observations made 88 days after placement. Cracking on each slab was categorized as minimal (no obvious cracks, some hairline cracking may be visible on close inspection), moderate (limited hairline cracking), or extensive/severe. Cracking patterns were reported separately only for the properly mixed products. For products mixed with excess water, cracking behavior was considered in conjunction with other performance criteria for a composite rating.

5.4.5 Substrate Bond

Cementitious self-leveling compounds rely in part on a tenacious bond to the substrate to control shrinkage. Two methods were used to assess substrate bond.

First, a half-core sample of each product (with concrete substrate attached) was subjected to moderate blows from a hammer in the laboratory along the leveling mortar-concrete interface. Nearly all of the fracturing occurred within both the leveling mortar and the substrate concrete, indicating a relatively strong bond. Only one of the core samples separated along the bond line; this sample was extracted from a sample with additional water added.

Second, tensile bond tests were also performed at two locations on each slab. A core was drilled but left in place, then a metal disk was bonded to the top of the core, and a measured load was applied and gradually increased to failure. The failure load was recorded, but the location of the fracture was of primary concern.

5.4.6 Compressive Strength

Three cubes measuring 1 inch on each side were cut from the drying shrinkage prism specimens, and tested for compressive strength. These test were performed in June 2003, several months after the specimens were cast (compressive strength values are typically specified at 28 days). Testing was based on ASTM C109/C109M-02; *Compressive Strength of Hydraulic Cement Mortars;* however, 1 inch cubes were used in lieu of the 2 inch cubes specified by the standard. The increased age of the specimens should have modestly increased compressive values obtained, while the smaller dimensions of the specimens would tend to yield lower values, with a net effect of lower values than if the standard was strictly followed. Nevertheless, the test provided good data for comparing the five products to each other.

5.4.7 Chemical and Petrographic Analysis

Chemical and petrographic analysis was conducted on three forms of each product: the unmixed powder (directly from the bag), hardened samples mixed with the correct amount of water, and hardened samples mixed with 1 liter of excess water per bag. The samples were evaluated by visual and microscopic examinations, X-ray diffraction, sulfur content determination (to evaluate gypsum content), and insoluble residue and losses on ignition. These analyses permitted a detailed compositional analysis of each product, which was compared to each manufacturer's published literature. The most important aspect of the chemical analysis was estimation of gypsum content. Gypsum occurs in relatively small quantities as a natural byproduct of cement production, and can help control drying shrinkage through concurrent ettringite formation. Excess gypsum, however, can cause delayed ettringite formation, a destructive expansive reaction that poses a risk to the long-term stability of the material, especially if it is exposed to moisture. Our analysis indicated that all of the tested products contain added gypsum to varying degrees.

6 DISCUSSION AND CONCLUSIONS

Each of the five products we evaluated exhibited a unique combination of properties and performance characteristics. One of the most significant findings is that none of the tested products comes close to meeting the Rubber Manufacturers Association's standard for MVER of 3 lbs. This is especially important because these products are marketed to allow quick turnaround; each manufacturer states that tile can be placed after no more than 24 hours. For instance, one manufacturer states that the MVER must not exceed 3 lbs., but this is mentioned in a separate section of the technical data. In contrast to the 3 lb. standard, our sample installation of the same manufacturer's product yielded 13.91 lbs. Further, this was the lowest MVER value measured among the five products. Based on these high MVER values, it appears that the leveling materials need much more curing time than the waiting time recommended by the manufacturer, which was 24 hours or less for each of the products we evaluated.

Also, all of the tested products contain sulfate in excess of the amount present in normal portland cement, thus indicating that the mix contains added gypsum or plaster and will react adversely to long-term moisture exposure. The same expansive reaction that counteracts drying shrinkage may also pose a risk for undesirable long-term expansion;

this is probably why most of the manufacturers appropriately recommend their product for interior use only. Nevertheless, even interior floors can be repeatedly exposed to moisture if they are cleaned via wet mopping, located near an outside entrance, or subjected to plumbing leaks, all of which are relatively common conditions. A useful follow up study may include evaluation of the long-term effects of moisture exposure on each product.

Other properties studied yielded more varied results. Two products were clearly the strongest overall performers in our study, based both on qualitative observations and laboratory data. A third product also performed well based on qualitative observations, but petrography and other laboratory studies yielded results that may be of concern, including a soft cement paste and moderate aggregate settlement that became more pronounced with the addition of excess water.

The remaining two tested products were notably poor performers in our study. Our initial observations of problems with these products during mixing and placement were confirmed during laboratory analysis. One of the products exhibited pronounced aggregate settlement, even with the correct amount of mixing water, and the other was the only product to become completely unusable when excess water was added. It is important to note that all manufacturers caution against using excess water. Nevertheless, because our studies indicate that the addition of excess water is a common practice among many contractors, we believe that tolerance of excess water is an important characteristic of any cementitious leveling material.

The flooring system failures described in this paper occurred not because of any inherent defect in the clay tile arch floor systems, but because these historic structural systems were not properly investigated and understood before embarking on a resurfacing program. Problems were compounded by improper application of modern leveling materials. Comparative laboratory studies of five cementitious leveling materials indicate that some, but not all, commercially available products should perform satisfactorily when properly used in accordance with the manufacturers' directions. The test protocol outlined in this paper provides guidance for the evaluation of leveling materials being considered.

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