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Method for the Comparative Evaluation of the Odor Barrier Properties of Coatings

Cliff Zlotnik, CR

Mold on Carpet: Can Proper Remediation of Fungus on Fibers be Accomplished?

Michael A. Pinto, CSP, SMS, CMP, CFO

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INTRODUCTION

Tile flooring failures that are observed as cracks, debonding and tenting are often attributed to moisture exposure, improper installation or heat exposure. We recognized that there are many installation deficiencies that also contributed to tile failure and that these reasons have been well documented (Barrett and Falls, 2012). However, we wanted to examine whether "sudden events" could influence tiles and cause bond failure when tiles were either competently or not competently bonded. Extended heat and moisture exposure greater than two days was not investigated. We also wanted to understand the discrete differences of tile bonding when influenced independently by temperature change or moisture exposure. We understood that the composition of floor tiles was different and that tiles may express varying movement attributes when exposed to temperature and/or moisture. This understanding encouraged us to examine a number of tile types. The test results demonstrated several unexpected features of tile behavior and identified unique differences of which we were unaware.

MATERIALS AND METHODS

As previously stated, this investigation required seven preparatory methods as described below.

Creating Fully Bonded (Competent) and Unbonded Tiles

The study began by identifying methods to produce unbonded tile specimens (12 × 12 inches) that could be tested in various percentages of unbonded tile exposed to temperature change and moisture absorption. The test protocol for creating unbonding or a separation below the tile considered four approaches:

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SYNOPSIS

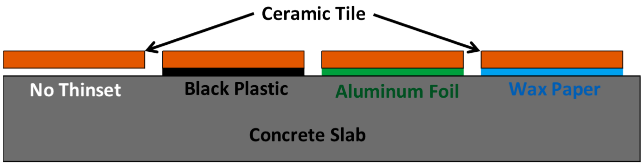
This study examined the occurrence of debonding and movement when various tiles were exposed to heat, cold and water, and whether debonding occurred. The study was conducted in two phases. The first phase was composed of two tasks: 1) securing tiles to a concrete substrate bound using thinset with varying percentages of unbonded surfaces beneath the tiles, and 2) exposing control (bonded) and test (unbonded) tiles to heat (heating pad and hot water up to 150ºF) and cold (-105ºF and 17ºF with salted ice and dry ice) to examine whether debonding occurred among control (100% bonded) tiles and various percentages of partially unbonded tiles. The second phase evaluated strain under laboratory-controlled conditions on individual tile panels. This phase measured movement as strain (1×10^{-6} strain was equivalent to 1.2×10^{-7} inches [3.05×10^{-7} cm]) among seven types of floor tile (ceramic, travertine, marble, porcelain, limestone, sandstone and slate) using strain gauges and thermocouples in response to heating, cooling and moisture exposure. During this phase the tiles being tested were not affixed to any substrate in order to isolate the tiles' responses. The study revealed the following results:

1. Floor tile movement is most profoundly affected by temperature.
2. Tiles (ceramic, porcelain, limestone, slate, travertine) immersed in water exhibited comparable movement to tiles at laboratory control conditions (75°F, 55% RH) (dry).
3. All tiles exhibited movement in response to cyclical operation (on and off) of the A/C system.
4. Temperature changes induced by heat (150°F) or cold (<17°F) caused tile movement in excess of control measurements in ceramic, porcelain, travertine and marble. These temperature ranges are not commonly encountered in the field and were utilized under laboratory conditions to demonstrate ranges of temperature possible in most natural environments.
5. All tiles, whether competently bonded or not, were vulnerable to debonding when exposed to abrupt temperature change.
6. Each tile type exhibited distinctive strain responses to moisture exposure and/or temperature change.
7. Sandstone and marble exhibited the highest movement response to moisture.

1. No application of thinset between the tile and the substrate.
2. Black plastic (2 mil) film.
3. Aluminum foil (Reynolds®).
4. Wax paper under the tile secured in place with a small amount of blue painter's tape.

The selection criterium was based on the clarity of the audible sound and handling ease. Among these, wax paper was determined to be the most effective (Illustration 1).

Illustration 1: Selection of layers applied to bottom surface of tile, wax paper yielded the best results.



Tiles of varying bonding coverage were prepared using random layouts of an inserted substrate (wax paper) to simulate 10, 25, 50, 75, 85 and 90% coverage. One-hundred percent mortar coverage controls were prepared without the use of inserted substrates. Each adhesive configuration was replicated to comprise 60 unbonded configurations and nine controls. The broad range of tile bonding percentages was implemented to represent real world scenarios where the tile installers often do not conform to Tile Council of North America (TCNA) standards.

Floor Preparation and Tile Selection

In the field, a 30-year-old, 240-square-foot (ft^2) section of concrete floor was prepared for tile installation by mechanical scarification using a diamond grinder to a surface similar to the broom finish (CSP-2) to level and expose the bare concrete for homogenous tile bonding to the floor. After scarification, the concrete floor was cleaned with soap and water followed by excess water extraction using a wet-dry vacuum and floor-fan drying. A moisture survey following the clean process showed normal moisture levels before thinset was applied (<14% WME).

In the laboratory under Phase 2, all testing procedures used individual tile types (12 × 12 inches) with no grout or mortar. Tiles were placed on copper plating (heat testing), plate glass (cold testing) and large shallow plastic lid (water exposure). Seven types of floor tiles (porcelain, slate, ceramic, limestone, marble, sandstone and travertine) were either applied to a concrete foundation or individually tested for temperature and moisture movement. One tile size was tested because the thermal expansion coefficient for all tile materials is linear. This means that small area measurements are directly related to large areas.

Tile Installation and Identification

In the field, the tiles were installed on the concrete floor, numbered and labeled according to the arrangement and test conditions (bonded and unbonded). Similarly, the tiles were marked on the top to show the location of the intended bonded and unbonded sections (concerns of bias were expressed about marking the unbonded portions of the tile). Using a chart that identified the tiles and the intended locations of the wax paper, the tiles were affixed to the floor using a thinset mixture (Merkrete, Thin Set, 710 Premium Set Plus), a tile trowel and tile installation as prescribed by the TCNA. Grout was used to fill the gaps between the tiles as prescribed by the manufacturer (SGM Tile Grout, White Polymer). For simplification, one type of mid-level-priced mortar and grout were used for the tile flooring installation to minimize the experimental variables. The tiles were positioned on the prepared floor in five sections. The first section accommodated the various types of tile (in duplicate) with select sizes of wax paper positioned beneath each tile. This section included the controls of nine ceramic tiles placed together (three rows of three) to evaluate the inherent stability and reaction between tiles competently bonded to the concrete foundation and abutted to one another (Photo 1). The remaining sections incorporated varying degrees of unbonded tiles to determine if reduced bonding results in more or less failure when exposed to temperature changes and moisture. The majority of tile flooring tested was ceramic due to the predominant usage in buildings. In the laboratory under Phase 2, floor tiles were tested individually and were not bonded to surfaces as described above. Floor tiles were tested in numerous ways for applicable scenarios observed in the field and laboratory to evaluate thresholds of failure.

Inducing Moisture Exposure

In the field, a large section of the tiled flooring (12 × 16 feet) was bordered with Styrofoam®

Photo 1: Various types of tile with select sizes of wax paper positioned beneath each tile and controls of nine ceramic tiles.

insulation and sealant applied to the floor and butted ends to create a watertight border approximately 3 inches in height (Photos 2 and 3).

Photo 2: Preparation of floor tiles equipped with strain gauges and thermocouples before flooding.

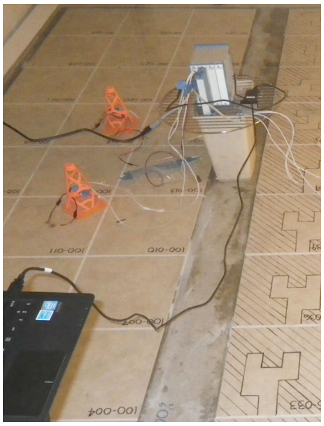


Photo 3: FLIR image of hot water (120°F) being discharged over floor tiles.

Four strain gauges and four thermocouples were affixed to selected tiles to monitor temperature change and movement continuously during testing. The water-tight border was flooded with ambient temperature water (80°F) for 48 hours, drained and the tiles checked for debonding by tapping (ASTM E1007) immediately after draining. The area was flooded again with hot water (120°F) directly from the base of a water heater and tiles subsequently tested again for bonding. A sudden water intrusion event can occur in several scenarios such as a water heater failure, flooding from the exterior, pipe burst, roof leak, etc. This test was conducted to simulate a worst-case scenario.

Moisture exposure in the laboratory testing was conducted using an individual tile type in duplicate by placing the tile inside a large plastic lid (24 × 24 × 1 inch). As described above, the tiles were equipped with a thermocouple and two strain gauges (placed in opposing directions) and then placed inside the lid before water was added. The tiles were not affixed to any surface so that the individual response of each type of tile could be measured. Either ambient temperature tap water or heated tap water (150ºF) was then gently poured inside the lid to encompass the entire perimeter of the test tile. In both field and laboratory conditions, care was taken to not wet the thermocouples or strain gauges.

Employing Strain Gauges and Thermocouples

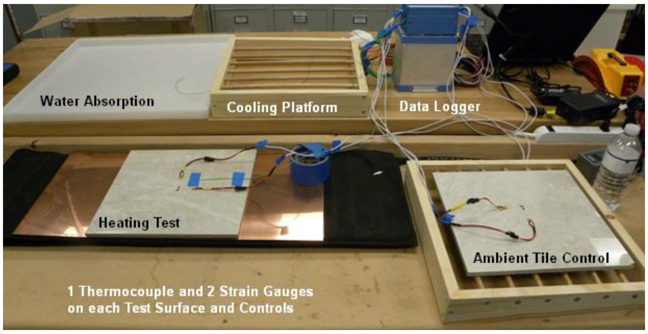
Strain gauges (120 ohm) were installed using cyanoacrylate (Gorilla Glue) and thermocouples (Type K) were taped onto the top surface. The strain data was recorded over time to determine if any variations occurred with no water or heat added.

Inducing Temperature Changes

Several techniques were used to induce tile temperature changes in the field and laboratory. Dry heating was accomplished by placing a commercial heating pad (Flexotherm, 150ºF) on a large wooden bench followed by a piece of sheet copper (12 × 24 inches), the bottom of the test tile was placed on the copper to ensure uniform heat distribution. Low ambient temperatures (16°F) (field test only) were attained by mixing 20lbs of ice and one pound of salt in a large plastic bag and placing it directly onto the tile. Extreme low temperatures (-105ºF) (field test only) were attained by purchasing dry ice from a grocery store, placing the dry ice directly on the tile and wrapping the assemblage with aluminum foil. Heating and cooling of tiles with water in the field was accomplished by flooding the tile test areas with either tap water (80ºF) or hot water directly from a water tank (120ºF). In the laboratory, heating and cooling was accomplished by adding tap water (80ºF) or heated water (150ºF) to the test.

Laboratory testing of the different types of tile was conducted to evaluate changes in the tile when exposed to temperature changes (convection and conduction) and liquid water (Photo 4). Ceramic tiles were selected for detailed evaluation of strain responses while all six types of tile were used for comparative tests. The heating pad was then turned "on" and allowed to heat the tile up to 150°F, documented by the thermocouple on the top surface. The temperature was recorded along with the strain data. When the tile reached 150°F the heating pad was turned "off" and allowed to return to ambient temperatures (72°F). The next test conducted on the tile was submersion in liquid water at ambient temperature. After the tile was placed inside the plastic container, liquid water was added to the edge of the tile submerging the entire edge and bottom. Liquid water was not allowed to cover the top surface of the tile; this

Photo 4: Laboratory test apparatus for exposing tiles to heat (150ºF) followed by moisture exposure.



was done to ensure no liquid water contacted the strain gauges. The tile was submerged for over three hours and the strain data recorded.

Measuring Movement (Strain)

Strain gauges were used for all thermal and moisture testing to provide a method to quantify the occurrence of movement. The strain gauges recorded the quantitative data of tile movement. The strain data varied depending on the influence of several variables: temperature, humidity, liquid water and air movement. Consistent strain measurements were more difficult to attain in the field than under laboratory conditions principally due to unstable temperatures. Once we recognized that the field temperature variations exhibited profound influence on tile movement, we continued our studies under laboratory conditions.

A strain gauge is a sensor that varies electrical resistance with an applied force, which can then be measured. When forces are applied to a stationary object, stress and strain are the result. Strain is caused by forces, pressures, torques, heat and structural changes of the material. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur. The definition of "strain" as applied in this paper consists of tensile and compressive strain demonstrated by positive or negative data. Accordingly, strain gauges were used to identify expansion and contraction of the test materials. For this experimental analysis, the unitless strain factor ($\varepsilon = \Delta L/L$) was used. A conversion to movement (ΔL) in inches was not used in this study due to the relativistic approach when comparing strain results, i.e., the strain of tile under control conditions versus the strain during heat or water application. For reference, one strain ($1 \times 10^{-6}\ \varepsilon$) was equivalent to 1.2×10^{-7} inches (3.05×10^{-7} cm) of movement. The amount of expansion under control conditions was 75 $\mu\varepsilon$; over a 20-foot length that was 0.018 inches (≈1/64 inch) (0.0457 cm per 6.1 m). The amount of expansion for 400 $\mu\varepsilon$ over 20 feet was 0.096 inches (<⅛ inch). We recognize that over a given length of tile and as strains change from temperature or water exposure, the expansion may contribute to tile debonding (Table 1).

Table 1: Tile movement over 20 feet using the maximum strain observed during testing.

Type of Tile	Max Microstrain ($\mu\varepsilon$)	Inches of Movement Over 20 feet	Equivalent Inch Fraction of Movement
Porcelain	150	0.036	1/32
Ceramic	400	0.096	3/32
Marble	600	0.144	1/8
Slate	200	0.048	3/64
Travertine	200	0.048	3/64
Limestone	75	0.018	1/64
Sandstone	5000	1.2	1 3/16

RESULTS

Tile Exposed to Moisture

The results of this study may conflict with many preconceived notions of tile failure. The effects of water on tile showed minimal to no changes in strain for travertine, ceramic, porcelain, limestone and slate. For the majority of buildings using these types of tiles, exposure to liquid water was found to induce no expansion or contraction in excess of control measurements. However, moisture exposure expressed a measureable effect on sandstone and marble and the abrupt temperature change induced by sudden moisture exposure can result in tile movement for porcelain, sandstone, ceramic, marble and travertine (Diagrams 1–3).

Tiles Exposed to Ambient Heat

Tiles were exposed to heat to determine the subsequent strain response. The data showed that the influence of temperature on porcelain, sandstone, ceramic, marble and travertine was sufficient to cause observable changes in the strain data. Limestone and slate demonstrated minimal change in strain over the four-hour period. The various strain responses as the temperature was increased to 150°F and then allowed to cool back to ambient conditions are shown in Diagram 3. The expansion and contraction of the different types of materials illustrated the differences in the crystalline structures and response to their inherent moisture content. Travertine demonstrated no apparent change in strain during the heating phase, after the heat was removed, movement did occur. Ceramic tile showed movement during the heating phase and abrupt movement when heat was removed. Porcelain slightly expanded during heating and contracted during the cooling phase. Only limestone and slate returned to zero strain or their starting point when they cooled back to ambient temperatures.

Control Measurements

As in all research, control measurements are as important as the test results. The control measurements are shown with a major and minor axis similar to the moisture exposure and heating tests (Diagram 4). The wave patterns observed in the diagrams demonstrate the influence of ambient temperature on the strain gauges and tile materials. As the laboratory air conditioning system cycled

Diagram 1: Strain when exposed to liquid water, sandstone exhibited unusual results (blue line).

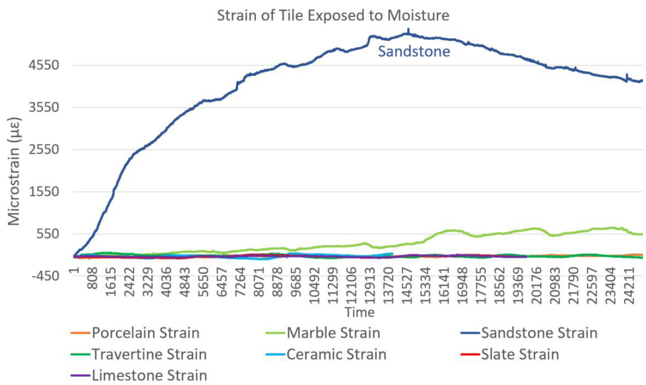


Diagram 2: Strain when exposed to liquid water (minus sandstone), marble exhibited excess strain (yellow line).

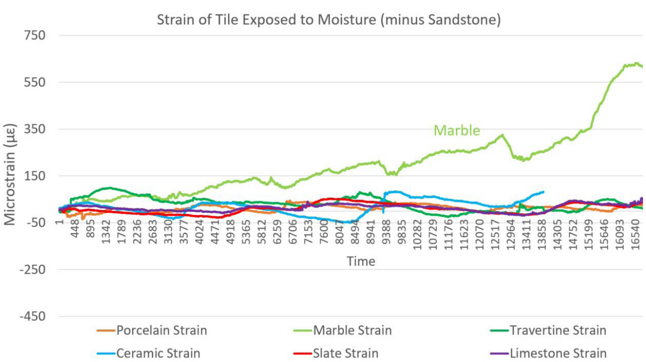


Diagram 3: Strain when exposed to temperature changes.

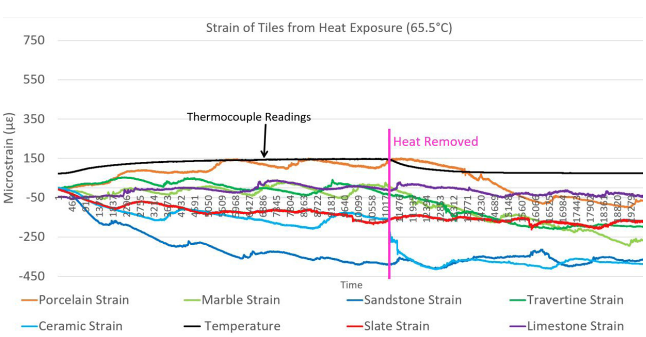
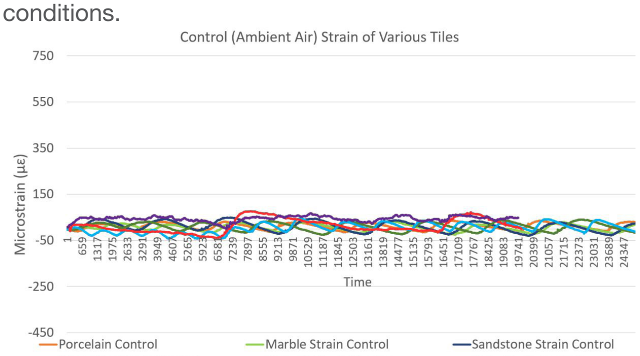


Diagram 4: Strain when exposed to ambient (control) conditions.

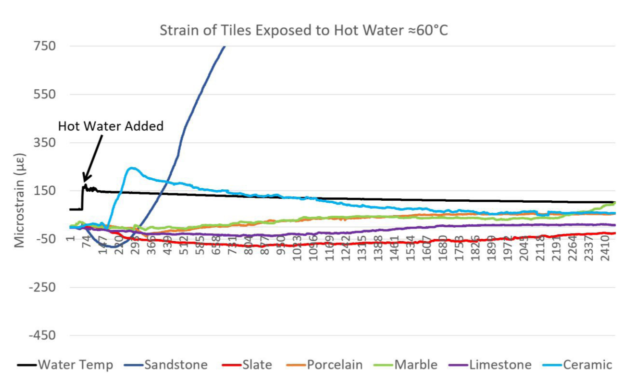


on and off, slight changes in the strain were documented. Slight temperature changes (±2°F) showed a microstrain (με) variation of less than ±75 με. When compared to the microstrain changes in the heated tile between 150 με (0.036″ per 20 feet) and -400 με (0.096″ per 20 feet), the oscillations in the temperature change caused by the air conditioning system were minor when compared to the measurements caused by the induced conditions. A comparison to the moisture exposure diagram was also prudent. Results following ambient temperature liquid water exposure showed a change in strain of ±75 με for travertine, ceramic, porcelain, limestone and slate, similar to the control results. The study also showed that the different tile types expressed unique movement characteristics during temperature changes.

Tiles Exposed to Hot Water

This test measured the influence of tile exposed to hot water. Water was heated (190°F) on a hot plate and poured gradually to a surface adjacent to the tile inside the sample enclosure. The water cooled to ≈140°F in less than one minute and then attained ambient temperature in 40 minutes. The hot water was added to simulate worst-case exposure scenarios. The rapid reduction in temperature reflected heat transfer. As previously noted, exposure to liquid water at ambient conditions resulted in no apparent changes (other than marble and sandstone). The heating of tiles using hot water yielded results lower than heating the tile on a heating pad. The abrupt temperature change in the ceramic tile resulted in a subsequent "spike" of movement that subsided as the water temperature reached ambient conditions (Diagram 5).

Diagram 5: Strain when exposed to hot water (≈140°F).



Torque on Tile

Torque was applied to ceramic tile for comparison to heat and moisture exposure results. Strain gauges were attached to the center surface of a ceramic tile in the *x* and *y* axis similar to all other tests. The specimen was then placed at the edge of a horizontal table and clamped down to resist movement during the testing. While the strain data was recorded with the data logger, torque was applied to the tile in the up (+z-axis) and down (-z-axis) directions for tension and compression of the surface. Torque was applied in 10-second intervals with increased torques (10, 20, 30 and 40 ft. lb.) using a torque wrench resulting in oscillation on the strain data scatter plot. To test the failure of tile and the corresponding strain, torque was applied until the ceramic tile failed. The results showed mechanical torque on tile exhibited profound movement similar to heating the tile (Diagram 6).

Diagram 6: Torque on tile measured in tension and compression of the surface layer.

Trim Expansion

Tile failure can often be attributed to the expansion of wood trim that abuts the cross section of a tile floor. The pressures exerted by wood products can exceed 100 lbs./in² after two to three hours of moisture exposure (Wells and Moon, 2015). The installation of tile flooring is purposefully applied as level as possible. However, in some cases the tile sections are not perfectly parallel to one another or perpendicular to the wood trim. When this condition occurs, the applied pressures from trim expansion may create a torque on the tile resulting in debonding or tenting. To evaluate this scenario a 12-inch by 12-inch ceramic tile specimen was abutted in between two sections of trim (Photo 5). Two tests were performed using pine wood trim and medium density fiberboard (MDF) and were allowed to soak for over 48 hours. As the wood expanded against the tiles, the pressures were applied and the strain gauge data recorded. Strain data analysis showed that tile compression occurred and was consistent with the characteristics of ceramic such as hardness and a high elastic modulus (stiffness or low ductility) (Diagram 7).

Photo 5: Laboratory trim expansion apparatus. Strain gauges arranged in x and y axis (2D) and covered to protect from air movement. Compression (1D) represented by red arrows.

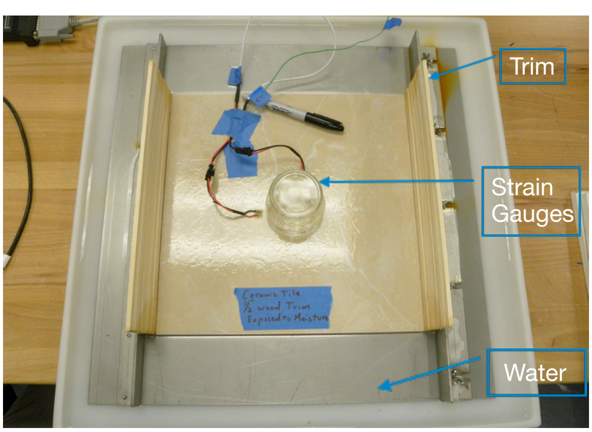
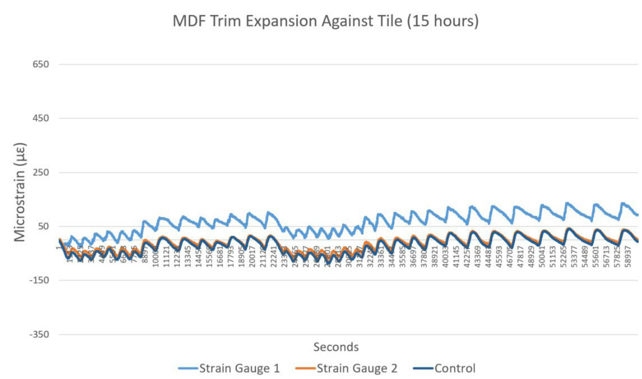


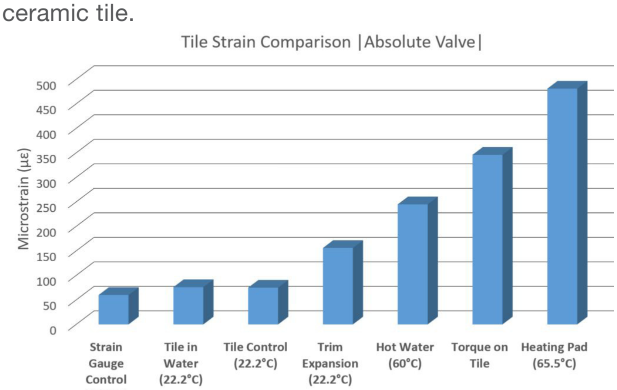
Diagram 7: Compressive strain on tile cross-section. Note: Strain gauge 1 increased and strain gauge 2 did not increase due to strain gauge orientation (red line). Oscillations are from cycling of air conditioning system.



Conclusions and Further Research

Several variables that act on tile flooring were tested to determine their contribution to tile failure. Although moisture exposure is commonly associated with tile failure, we found that moisture alone expressed no impact on tile movement (except sandstone and marble). The primary contributor to movement was temperature change (Table 2).

Table 2: Comparison of strain data for tested variables on ceramic tile.



Several experiments were conducted on various types of tile. During liquid water exposure at ambient conditions, no apparent movement occurred to porcelain, ceramic, travertine, limestone and slate when compared to control measurements. Marble and sandstone showed measurably more movement during moisture exposure. The strain results indicated the primary movement occurred from temperature change caused by fluctuations in the laboratory temperature during air conditioning cycling.

Tile flooring failure analysis must consider a number of contributing factors. Installation techniques, temperature changes, abrupt hot water leaks, exposure to sun light, subfloor movement, trim swelling and water erosion can all contribute to the failure of tile.

The authors recognize the tile failure is associated with some form of movement. Temperature change and installation errors represent common causes of movement and tile failure. Water exposure alone to tile materials did not elicit measureable change.

Sandstone and marble exhibited excess movement when exposed to liquid water at any temperature. Field evaluation of these tiles should consider their inherent movement during moisture exposure.

The interaction of grout and thinset to tile bonding in response to temperature change and moisture exposure offers promising research opportunities. The authors recognize that thermal expansion and absorptive qualities of various thinsets and grouts may influence changes in tile movement.

Only one component (tile) among a four component floor system (grout, tile, thinset, foundation) was studied. Further research is necessary to identify how all components interrelate in response to temperature and moisture changes.

Error

Inherent variability of test materials and procedures were recognized and minimized during the tile testing. Influences such as temperature, humidity, strain gauge imperfections and "noise" all contributed minor variations in the collected strain data. Temperature changes and air movement in the laboratory environment represented a large contribution to oscillations in the strain data. This was determined as cycling of the air conditioning system. The error from the data logger was represented as the logarithmic conversion of analog to digital data and was reduced to sufficient levels so actual strain results were not concealed in the correction factor. During the laboratory heating process, the inability to attain baseline conditions may be attributed to a varying moisture content in the tile and/or altered performance of the strain gauge. CSQ

Although moisture exposure is commonly associated with tile failure, we found that moisture alone expressed no impact on tile movement (except sandstone and marble). The primary contributor to movement was temperature change.

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