MATERIALITY OF TILE: DESIGN IMPLICATIONS OF TILE'S VISUAL, PHYSICAL, AND ENVIRONMENTAL ATTRIBUTES

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SUMMARY

Ceramic tile in all its variety is widely acknowledged as among the most beautiful, durable, and healthy finishes available for commercial and residential projects, but what is it exactly about tile that makes it a desirable and high-performing material? This paper, organized in three sections, will take a detailed look at the objective criteria set forth in ANSI and ASTM standards that establish the visual, physical, and environmental performance of tile and tile assemblies in the context of design.

The aesthetics portion will address visual attributes of the tile including uniformity of color, shade, and texture, as well as dimensional stability, warpage, wedging, and facial defects. This section will analyze each of these criteria through the lens of how they are tested and measured per U.S. standards, and it will address implications of these visual variables on the design of the tile assembly.

The physical considerations portion of the paper will focus on how the tile behaves physically including its water absorption, durability, and bond strength. This section will analyze each of these criteria through the lens of how they are tested and measured per U.S. standards, and it will address implications of these physical variables on the design of the tile assembly.

The final portion of the paper will examine the performance of the finished tile assembly in its installed environment, and how the visual and physical properties of the materials work in concert to achieve the assembly-wide attributes of health benefits, ease of maintenance, fire and smoke resistance, watertightness, and design versatility. This section will analyze these criteria through the lens of how they are tested and measured per U.S. standards where applicable, and it will address implications of these environmental variables on the design of the tile assembly, and the overriding impact qualified labor has on every tile installation.

When considered together, the visual, physical, and environmental attributes of tile inform the materiality of tile as a finish assembly. This paper will define and describe the materiality of tile in a way that is meaningful to the design professional, specifier, owner, and end user of the tile installation to educate these stakeholders on the attributes of tile that most heavily impact design decisions.

PART 1: VISUAL ATTRIBUTES

The intrinsic beauty of ceramic tile has made it a desirable material for thousands of years. When manufactured to U.S. standards, tile provides an appearance that is not only beautiful, but visually predictable. The appearance of a tile installation is largely dependent on the visual qualities of the tiles themselves, which are established by ANSI A137.1, *American National Standard Specification for Ceramic Tile*. Tile's physical characteristics are quantifiable and measurable by the standard, which helps to set a benchmark expectation for the visual quality of the completed tile installation. Aesthetic criteria established by A137.1 include limitations for facial defects, uniformity of color, shade, and texture, dimensional stability, and limitations for warpage and wedging. This article will analyze each of these criteria through the lens of how they are tested and measured, and the impact they have on the finish tile assembly. The scope of this section covers aesthetic criteria for the types of tile addressed in ANSI A137.1: mosaic, quarry, pressed floor, glazed wall, and porcelain tiles.

1.1 VISUAL INSPECTION

Standard grade tiles, also known as first grade tiles, are tiles that meet all the inspection and testing criteria set forth in ANSI A137.1. Before any other testing, tile manufacturers visually inspect a sample of the lot size for facial and structural defects. Facial defects are portions of the tile's surface observed to detract from the appearance or serviceability of the installed tile. Examples include pinholes, contaminants, chips, cracks, scratches, and glaze application errors. Structural defects are cracks or laminations visually observed in the body of the tile that detract from the appearance and/or the structural soundness of the tile. For a tile to be sold as standard grade, the sample must be free of facial and structural defects per the sampling plan specified.

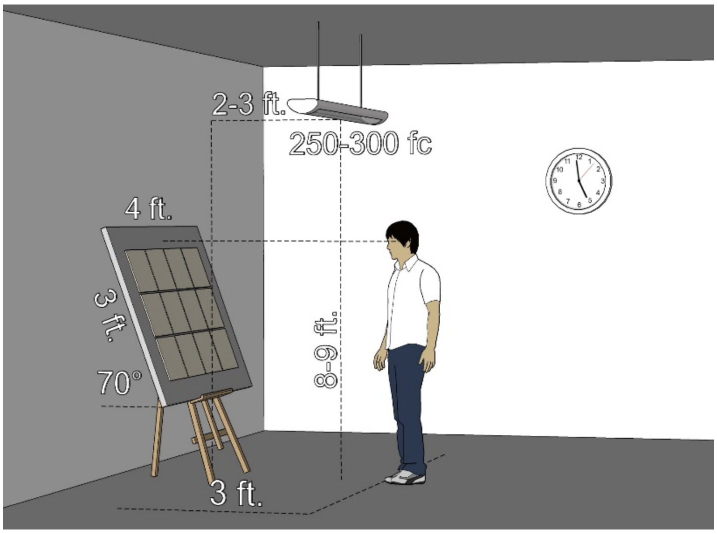

Fig 1. *Visual inspection of tile*

The procedure for evaluating tiles for facial defects requires a sample array of tiles to be mounted to a light grey viewing board at least 36 in. high x 48 in. long supported by an easel or framework holding the board 70 degrees from horizontal, with the top edge of the tile array at or below the evaluator's eye level. A white fluorescent lamp emitting 250-300 footcandles shall be positioned 8-9 feet above the floor and 2-3 feet from the front edge of the viewing board. The evaluator stands erect, three feet from the bottom of the viewing board, aligned with the center of the viewing board. (Fig. 1) The evaluator must not be color blind and must have 20/20 to 20/40 vision. Viewing time is 6 seconds per square foot of tile array evaluated. If the sample passes visual inspection, it moves on to subsequent testing and may be sold as standard grade tile. If the sample is found to contain excessive facial defects, the inspection may be repeated from a distance of ten feet instead of three feet, and if accepted from ten feet, it may be sold as second grade tile.

1.2 UNIFORMITY OF COLOR, SHADE, AND TEXTURE

Once the grade is established, tiles undergo additional testing, including evaluation for aesthetic classification. Consistency in a tile's appearance varies among individual product lines. Some tiles are manufactured to have a uniform appearance in color, shade, and texture, while other tiles are manufactured to intentionally display a slight or even drastic variation of appearance. Color can vary in intensity, brightness, hue, and saturation, and texture can vary to resemble natural stone, wood, or a variety of other products.

To help design professionals specify tile that meets their expectations of visual uniformity, ANSI A137.1 defines five distinct aesthetic classes: V0, V1, V2, V3, and V4. The letter "V" indicates "variation," with the numbers quantifying the degree of variation of appearance. The higher the number, the more variation.

ANSI A137.1 provides descriptions for each aesthetic class. Tiles meeting V0 show a "very uniform appearance," indicating that pieces of the same shade value are very uniform and smooth in texture. Tiles meeting V1 show a "uniform appearance," meaning differences among pieces from the same production run are minimal. Tiles meeting V2 show "slight variation," indicating clearly distinguishable differences in texture and/or pattern within similar colors. Tiles meeting V3 show "moderate variation," so while the colors and/or texture present on a single piece of tile will be indicative of the colors and/or texture expected on other tiles, the degree of colors and/or texture on each piece may vary significantly. Tiles meeting V4 show "substantial variation," so one can expect random color and/or texture differences from tile to tile, even to the extent that one tile may have totally different colors and/or texture than other tiles.

Because of this allowable variation, particularly among tiles in the V3 and V4 classes, several preemptive measures are recommended to manage expectations of the design professional and the end user. Tile should be selected based on evaluation of physical samples rather than from images. Several pieces of full-sized tile should be examined to understand the range of colors and textures. In some cases, a dry-laid mockup is helpful to evaluate the layout and blend prior to installation. For tiles with moderate and substantial variation, installers should blend tile from several cartons during installation.

1.3 DIMENSIONAL STABILITY

The appearance of a tile installation is affected by the dimensional stability of the tiles, in other words, how consistent the size is from tile to tile. Uniformly sized tiles can be installed with tighter grout joints, and tiles with greater dimensional variation require wider grout joints. It is also easier for installers to maintain alignment of grout joints and uniformity of grout joint width when the tiles are more dimensionally stable. ANSI A137.1 describes allowable dimensional variation as "caliber range." Caliber range is defined as variation from average facial dimension of sample, tested per ASTM C499, *Standard Test Method for Facial Dimensions and Thickness of Flat, Rectangular Ceramic Wall and Floor Tile*.

1.3.1 CALIBER RANGE

Depending on the type, tiles may be classified in up to three sizing categories based on their caliber ranges. **Rectified** tile has the tightest tolerance. A rectified tile is a tile that has had all edges mechanically finished to achieve a relatively precise facial dimension. **Calibrated** tile has the next tightest tolerance. A calibrated tile is a tile that has been sorted to meet a manufacturer's stated caliber range. **Natural** tile is the least dimensionally stable. A natural tile is neither mechanically sized nor sorted. According to ANSI A137.1, porcelain tile and glazed wall tile may be either rectified or calibrated; pressed floor tile may be either rectified, calibrated, or natural; Quarry tile and mosaic tile are not categorized.

Let's look at the acceptable caliber range for calibrated pressed floor tile using a tile of nominal 24 in. dimension as an example. Note that the actual dimension of nominal 24 in. tile may vary by as much as ±4.00%, and this value varies by manufacturer. In our example, we will use 23 7/8 in. as the actual size. The values below can be found in Table 8 of ANSI A137.1.

Fig 2. *Allowable caliber range*

For calibrated pressed floor tile ≥ 6 in., allowable caliber range is ±0.50% or ± 0.08 in., whichever is less. Therefore, a nominal 24 in. pressed floor tile that is calibrated may vary ±0.08 in. (±5/64 in.). So, the actual dimension of 23 7/8 in. may be as small as 23 51/64 in. and as large as 23 61/64 in. (Fig. 2)

Allowable caliber ranges for rectified and natural pressed floor tile can be found elsewhere in Table 8 of ANSI A137.1, and values for mosaic, quarry, glazed wall, and porcelain tile can be found in Tables 6, 7, 9, and 10, respectively. By understanding acceptable caliber ranges, the design professional or end user can reasonably predict how the finished installation will appear with respect to grout joint width, uniformity, and alignment.

1.3.2 WARPAGE

Most consumers of tile expect a relatively flat installation, which assumes the substrate is flat and the tiles themselves are flat. Tile installation standards have clearly defined tolerances for the required flatness of substrates, and tile material standards set forth warpage limitation criteria for tiles. Tiles may be slightly warped from edge to opposite edge (edge warpage), or from corner to opposite corner (diagonal warpage). The test for measuring warpage is ASTM C485, *Standard Test Method for Measuring Warpage of Ceramic Tile*. Inherent warpage of tile can affect the installation's flatness, lippage between tiles, and acceptable offset bonding patterns that may be used.

Similar to allowable caliber ranges, allowable warpage depends on the type of tile and the sizing category. As an example, we will again look at a calibrated pressed floor tile of a 24 in. nominal dimension, 23 7/8 in. actual dimension. The values below can be found in Table 8 of ANSI A137.1.

For calibrated pressed floor tile ≥ 6 in., allowable warpage is ±0.50% or ± 0.08 in., whichever is less. Therefore, a nominal 24 in. pressed floor tile that is calibrated may be "cupped," or warped in either direction as much as 0.08 in. (5/64 in.) from edge to edge or diagonally. (Fig. 3)

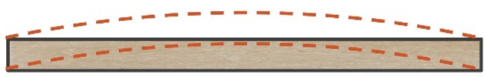

Fig 3. *Allowable warpage*

Allowable warpage for rectified and natural pressed floor tile can be found elsewhere in Table 8 of ANSI A137.1, and values for mosaic, quarry, glazed wall, and porcelain tile can be found in Tables 6, 7, 9, and 10, respectively. Armed with an understanding of acceptable tile warpage, the design professional or end user can reasonably predict how the finished installation will appear with respect to general flatness and lippage.

1.3.3 WEDGING

Fig 4. Allowable wedging

Tiles are normally pressed in dies having true 90° angle construction. However, minor variations in die fill, compacting pressure, and heat treatment can result in finished tile with acute and obtuse angles. This out-of-squareness results in a difference in length of opposite sides, creating a tile with the appearance of a keystone or wedge. This difference in length is known as wedging. Excessive wedging presents difficulties in the installation of tile. ANSI A137.1 sets maximum wedging criteria, citing as the test method ASTM C502 *Standard Test Method for Wedging of Flat, Rectangular Ceramic Wall and Floor Tile*.

To determine allowable wedging, we will again look at the example of a calibrated pressed floor tile of 24 in. nominal dimension, 23 7/8 in. actual dimension. The values below can be found in Table 8 of ANSI A137.1.

For calibrated pressed floor tile ≥ 6 in., allowable wedging is ±0.50% or ± 0.08 in., whichever is less. Therefore, a nominal 24 in. pressed floor tile that is calibrated may have opposites sides that vary by ±0.08 in. (±5/64 in.). So, the actual dimension of 23 7/8 in. may be as small as 23 51/64 in. on one side and as large as 23 61/64 in. on the opposite side. (Fig. 4)

Allowable wedging for rectified and natural pressed floor tile can be found elsewhere in Table 8 of ANSI A137.1, and values for mosaic, quarry, glazed wall, and porcelain tile can be found in Tables 6, 7, 9, and 10, respectively. With an understanding of acceptable wedging, the design professional or consumer can reasonably predict how the finished installation will appear with respect to parallel lines in tiles and grout joints.

1.4 BEAUTY: IN THE EYE OF THE BEHOLDER?

The vast realm of ceramic tiles manufactured today are capable of expressing a variety of design motifs, from exacting, precise, and predictable to irregular, random, and surprising. Whatever the project's visual requirements, design professionals can rely on the established methods set forth in ANSI A137.1 for measuring and classifying the aesthetic attributes of tile. In the hands of an educated design professional and qualified tile installers, tile is capable of achieving any design aesthetic.

PART 2: PHYSICAL ATTRIBUTES

Not only is tile beautiful, but it performs reliably and predictably under many loads and usage applications. Performance of tile is measured using a variety of ANSI and ASTM test methods. This section will focus on tile's properties of water absorption, durability, and bond strength through the lens of how they are tested and measured per U.S. standards, and the implications of these physical variables on the design of the tile assembly.

2.1 WATER ABSORPTION

Water absorption of tile is an important characteristic because it is a general measure of a tile's durability. Water absorption rates affect a tile's performance in freeze/thaw cycling, thermal shock, and other extreme measures the tile may be exposed to. ANSI A137.1 defines four classifications of ceramic tile based on water absorption rates. Impervious tiles have water absorption of 0.5% or less. Vitreous tiles have water absorption of more than 0.5% but not more than 3.0%. Semi-vitreous tiles have water absorption of more than 3.0% but not more than 7.0%. Non-vitreous tiles have water absorption of more than 7.0% but not more than 20%.

Absorption characteristics of tile are a function of the proportion of raw materials, methods of mixing and grinding, methods of forming (pressed or extruded), methods of drying, and methods of firing. For a tile to be classified as porcelain, it must have 0.5% absorption or less. Typically, porcelain tile incorporates a higher proportion of Kaolin clays, also known as China clays, relative to other clays and Feldspar, Silica, Talc, Calcite, Quartz, and other raw materials. The temperature and length of firing also affects a tile's porosity and water absorption.

2.2 DURABILITY

Ceramic tile is a durable material able to withstand heavy loads, high impact, and the wear that comes with decades of continual use. This section will examine what it means to be a durable material, and how durability is measured and quantified.

The initial measure of performance for a tile assembly is the durability of the tiles themselves. ANSI A137.1 and the various ASTM and ISO tests it references have clearly defined criteria for abrasion resistance (ASTM C1027 *Standard Test Method for Determining Visible Abrasion Resistance of Glazed Ceramic Tile* and ASTM C1243 *Standard Test Method for Relative Resistance to Deep Abrasive Wear of Unglazed Ceramic Tile by Rotating Disc*), breaking strength (ASTM C648 *Standard Test Method for Breaking Strength of Ceramic Tile*), thermal shock (ASTM C484 *Standard Test Method for Thermal Shock Resistance of Glazed Ceramic Tile*), and freeze/thaw cycling (ASTM C1026 *Standard Test Method for Measuring the Resistance of Ceramic and Glass Tile to Freeze-Thaw Cycling*). Each of these factors contribute to the overall durability of the tile, which is the first line of defense for the assembly. Specifying good quality tiles compliant with ANSI A137.1 will not guarantee a durable assembly, but it's a very good start.

Installation methods also impact performance. As important as it is to have durable tiles, it is also imperative that the tile and everything behind it function together as a durable assembly. The Tile Council of North America (TCNA) Handbook publishes a system of performance levels, also known as performance ratings or service ratings, which are classifications of the assembly that indicate how well it will perform - in other words, how durable it will be.

The TCNA Handbook lists five service rating designations for tile floor assemblies, each correlating to a category of use based on the types of loads expected. **Extra Heavy** is the service rating for extra heavy and high impact use in food plants, dairies, breweries, and kitchens. It requires quarry tile, packing house tile, or tile designated by the tile manufacturer for the intended application. **Heavy** is the service rating for shopping malls, stores, commercial kitchens, work areas, laboratories, auto showrooms, and service areas, shipping/receiving areas, and exterior decks. **Moderate** is the service rating for normal commercial and light institutional use in public spaces of restaurants and hospitals. **Light** is the service rating for light commercial use in office spaces, reception areas, kitchens, and bathrooms. **Residential** is the service rating for residential kitchens, bathrooms, and foyers.

Every floor tile installation method appearing in the TCNA Handbook falls within one of these performance ratings. For example, method F122 *Interior floor thin-bed method over on-ground concrete with waterproof membrane* is classified as having a Moderate service rating. The service ratings are found in the TCNA Handbook's Floor Tiling Installation Guide section as well as in the methods themselves. The service rating designated for each method does not exceed the performance of the weakest component in the respective method. For example, depending on its density and thickness, the presence of a membrane may adversely affect the performance of an assembly, thereby factoring into the method's service rating.

The Handbook's Floor Tiling Installation Guide instructs readers to first determine the required performance level of the assembly, and then choose the installation method that meets or exceeds the desired performance. For example, if the project is a retail store, the required service rating is Heavy, and therefore it should use method F103, F103B, F104, or F121. Additionally, any method classified as Extra Heavy would also be acceptable. Methods designated with Moderate, Light, or Residential service ratings would not be acceptable for a retail store. Note that design professionals may opt to design assemblies that do not appear in the TCNA Handbook, and therefore will not have service ratings assigned. Since the TCNA Handbook is only a guide and not a comprehensive compilation, this is acceptable as long as rational design practice is followed.

Now that we know that service ratings are key indicators of a tile assembly's performance, let's look at the science behind these designations. The performance levels designated in the TCNA Handbook are based on ASTM C627, *Standard Test Method for Evaluating Ceramic Floor Tile Installation Systems Using the Robison-Type Floor Tester*, commonly known as the Robinson Floor Test.

The Robinson Floor Test provides a standardized procedure for evaluating performance of ceramic floor tile installations under conditions similar to specific real-world usages. It is intended to evaluate complete ceramic floor tile installation systems for failure under dynamic loads. The method can test a variety of substrates including concrete and wood, various underlayments and membranes, and various installation methods and setting materials. The testing machine uses a three-wheeled cart that rotates about its center on top of a section of a tile floor assembly to be tested. The cart's wheels are attached to swivel casters and are configured as an equilateral triangle. There is a vertical rod above each wheel that accommodates weights of up to 300 pounds per wheel, which are stacked in increasing increments during the test. A 3/4-horsepower motor drives the assembly, and the cart rotates at a rate of 15 revolutions per minute creating a wheel path 30 inches in diameter along the tile floor. (Fig. 5) The machine tests the assembly to failure over the course of up to fourteen cycles of cart travel, using heavier loads and/or harder wheels with each successive cycle. Damage is assessed after the completion of each cycle. Cycles 1 through 4 use soft rubber wheels and are 60 minutes in duration with weights of 100-300 pounds over each wheel. If the assembly has not yet failed, cycles 5 through 8 use hard rubber wheels and are also 60 minutes long with 100-300 pounds over each wheel. If the assembly has continued to survive, cycles 9 through 14 use steel wheels and are 30 minutes long with weights of 50-300 pounds over each wheel. Damage is quantified as chipped tile, broken tile, loose tile, spalled grout joint, cracked grout joint, or powdered grout joint. ASTM C627 includes clear guidelines on how to quantify the damage to the tile and grout joints in the wheel path, and how much damage constitutes failure of the test. However, the standard does not interpret the test results; that is done in the TCNA Handbook.

Fig 5. *Robinson floor test*

The Handbook's Floor Tiling Installation Guide establishes a correlation between a method's Robinson Floor Test result and its service rating. Assemblies passing cycles 1 through 3 are rated Residential. Assemblies passing cycles 1 through 6 are rated Light. Assemblies passing cycles 1 through 10 are rated Moderate. Assemblies passing cycles 1 through 12 are rated heavy. And assemblies passing cycles 1 through 14 are rated Extra Heavy. Every floor method in the Handbook has undergone the Robinson Floor Test and has been assigned a service rating based on the results.

2.3 ENVIRONMENTAL EXPOSURE

In addition to tile's ability to perform under a variety of loads, tile assemblies can also stand up to various environmental factors when designed and installed properly. The TCNA Handbook lists categories of use for residential and commercial installations, collectively known as **Environmental Exposure Classifications**. Commercial applications are generally more demanding of the assembly, and commercial cleaning and maintenance practices typically generate greater water exposure than residential practices. The environmental exposure classifications consider the assembly's proximity to moisture, humidity, and temperature.

A partial list of the commercial environmental exposure classifications follows. **Com1 (Commercial Dry)** includes tile surfaces that will not be exposed to moisture or liquid except for cleaning purposes. Examples include floors in areas with no direct access to the outdoors and no wet utility function such as hallways, dry area ceilings, accent walls, and corridor walls. **Com2 (Commercial Limited Water Exposure)** includes tile surfaces that are subjected to moisture or liquids but do not become soaked or saturated. Examples include floors where water exposure is limited and/or water is removed, as in bathrooms and locker rooms. Some backsplashes, bathroom walls, other walls, and wainscots may also fall in this category. **Com3 (Commercial Wet)** includes tile surfaces that are soaked, saturated, or regularly and frequently subjected to moisture or liquids. Examples include shower and tub floors and walls, enclosed pool areas, natatoriums, public communal showers, and some commercial kitchen floors and walls. **Com4 (Commercial High Humidity, Heavy Moisture Exposure)** includes tile surfaces that are subject to continuous high humidity or heavy moisture exposure, especially in enclosed areas. Examples include continuous use steam showers and steam room walls and ceilings. **Com5 (Commercial High Temperature ≥125°F)** includes tile surfaces frequently subjected to water or vapor greater than or equal to 125°F. Examples include commercial saunas, furnace and boiler areas, and some commercial kitchen floors and walls. **Com6 (Commercial Exterior)** includes tile surfaces exposed to exterior conditions. Examples include exterior walls, balconies, and decks. Finally, **Com7 (Commercial Submerged)** includes tile surfaces exposed to continuous water submersion in interior or exterior conditions. Examples include swimming pools, water features, and fountains.

Each installation method appearing in the TCNA Handbook has been assigned one or more environmental exposure classifications, indicating that the method is expected to perform well in those exposures. For example, method F122 *Interior floor thin-bed method over on-ground concrete with waterproof membrane* is rated as Res1/Com1, Res2/Com2, Res3/Com3, and Res4/Com5. The classifications are found in the TCNA Handbook's Environmental Exposure Classification section as well as in the methods themselves. Unlike the service rating categories which are connected to ASTM C627, the environmental exposure classifications are not tied to any test, rather they are based on the tile industry's assessments of different assemblies that have proven to be durable in harsh environments.

Design professionals may opt to design assemblies that do not appear in the TCNA Handbook, and therefore will not have environmental exposure classifications attached. Since the TCNA Handbook is only a guide and not a comprehensive compilation, this is acceptable as long as rational design practice is followed. When selecting an installation method, design professionals are urged to consider the assembly's exposure to moisture, humidity, and extreme temperatures; and for exterior applications, to consider local climate and conditions including temperature, temperature fluctuations, humidity, humidity fluctuations, and freeze/thaw cycling.

2.4 BOND STRENGTH

There are few factors as important to a good tile installation as bond. For a tile assembly to perform well over time, it must remain adhered to the substrate. Tile standards have clear requirements for bond strength, and there are a few ways to test for bond. Although we often discuss bond strength, it is shear strength that ensures the ability of the tile to adhere to a surface.

Shear is a force that produces a sliding failure along a plane that is parallel to the direction of the force. In a tile assembly, shear often occurs between the tile and the substrate. An example of shear acting on a tile assembly is a floor spanning between two beams which deflects under a load. At the area of greatest deflection, between the beams, the substrate is undergoing compression and is becoming shorter. Conversely, immediately over the beams the substrate is in tension and is becoming longer. The tile wants to stay the same size, but the shear forces acting on it from the substrate are in danger of causing the tile to become unbonded if the shear bond strength of the mortar is not sufficient. (Fig. 6)

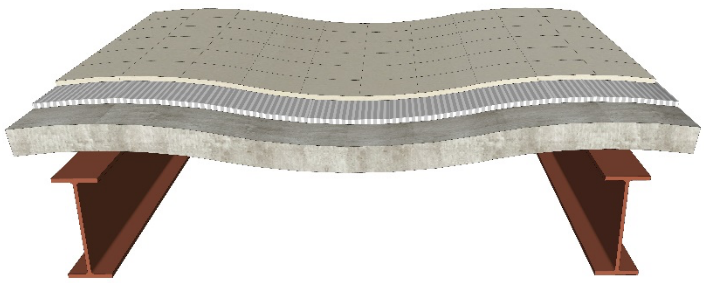

Fig 6. *Slab undergoing shear forces*

Another example of tile in shear is a tall building with an adhered tile facade undergoing a wind load causing the building to bend. The windward side of the building elongates creating shear forces which the tile assembly must resist. As in the previous example, if the shear strength of the tile or the mortar is insufficient, the bond could fail.

Shear bond strength is the maximum shear force an assembly can sustain before the bond fails. Shear bond strength is measured in pounds per square inch (psi) and is calculated by dividing the load at failure by the bonded area. We can avoid failures in shear bond by using tiles and mortar that meet minimum bond strength requirements as specified in ANSI standards, by correct application of bonding mortar including minimum coverage and embedment practices, and by making sure the substrate is suitable for bonding.

Shear bond requirements for tile assemblies may be analyzed a few different ways. (Fig. 7) It is unlikely that the tile itself will shear, but under extreme conditions, shearing of a very soft natural stone or tile could occur. For ceramic tile installations, it is more likely that failure may occur at the bond between the tile and the mortar or between the mortar and the substrate. It is also possible that the mortar itself may fail due to loss of cohesive strength when subject to shear forces. Finally, cohesive failure could occur within the substrate itself. Careful material selection and design and installation safeguards should be taken against each of these potential types of failures.

ANSI A137.1 specifies minimum bond strength of 50 psi for tiles when tested in accordance with ASTM C482 *Standard Test Method for Bond Strength of Ceramic Tile to Portland Cement Paste*. This is a test of the tile's ability to bond to an adhesive of portland cement paste, which is bonded to a generic backing of a cured cement mortar bed. It only measures failure between the tile and the cement paste adhesive, not failure between the cement paste and the setting bed, nor failure of the setting bed itself. This test is a measure of the bond strength of the tile itself. Reference to ASTM C482 is also made in TMS 402, *Building Code Requirements for Masonry Structures*, in the adhered veneer section, stating "Adhesion developed between adhered veneer units and backing shall have a shear strength of at least 50 psi."

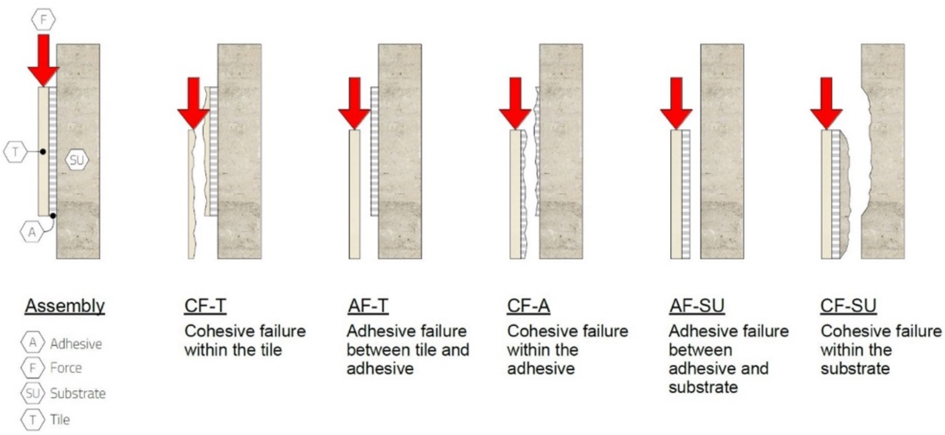

Fig 7. *Modes of shear failure*

In addition to sufficiently strong tiles, appropriately strong mortar must also be used to prevent shear bond failure, and it must be applied to minimum coverage requirements. The ANSI standards for dry-set mortar (ANSI A118.1), modified dry-set mortar (ANSI A118.4), and improved modified dry-set mortar (ANSI A118.15) each specify requirements for shear strength of the respective mortars. These tests are described as testing "shear strength of mortar to tile." Adherence to these requirements guards against failure of the bond between mortar and tile.

As an example, let's look at the requirement for shear strength specified in ANSI A118.15. The standard requires the seven-day shear strength for improved modified dry-set mortar to be a minimum of 450 psi when it is used with glazed wall tile, 300 psi when used with porcelain, or 150 psi when used with quarry tile. Mortar manufacturers must test their materials to these requirements in order to market them as compliant with ANSI A118.15. This test is done in a laboratory using two 1 in. x 1 in. tiles with a 1/8 in. mortar joint and applying a load until the joint fails. This is a test of the mortar's capability to bond to the tile. A similar test is used for ANSI A118.4 modified mortars, but with slightly lower required minimum strengths.

PART 3: ENVIRONMENTAL ATTRIBUTES

So far, we have discussed tile's visual properties of uniformity of appearance, dimensions, flatness, and squareness, and tile's physical properties of water absorption, resistance to extreme loads, and resistance to extreme moisture, humidity, and temperature. This section will address the installed tile assembly, looking beyond the properties of the tile itself, and examining performance of the assembly in the context of its environment.

3.1 HEALTH BENEFITS

Due to the COVID-19 pandemic, the construction industry has a renewed focus on maximizing the use of interior finishes that are anti-microbial and easy to clean. Ceramic and porcelain tile have historically been used in healthcare and other commercial applications for exactly this reason, as well as the many others benefits they offer. Tile is an impervious, inorganic material naturally resistant to microbes and the spread of infections. When we look at tiled surfaces, it is desirable to minimize intersections that may trap dirt, moisture, and debris, and to provide continuity along the change of plane. A cove base, also known as a sanitary base, or the use of concave profile strips are effective details for transitioning a wall to a floor while providing ease of cleaning and minimizing opportunities for germs.

3.2 EASE OF MAINTENANCE

Tile installations, including the tile and grout, naturally resist dirt and stains, and when installed properly they require little effort to maintain. Sweeping with a broom or electrostatic cleaning tool, e.g. Swiffer, is the first step to keeping a tile surface free of dust and debris. If required, wiping or mopping with clear, clean water, or in some cases a neutral cleaner or mild detergent, is sufficient to maintain tile surfaces. Harsh cleaners are generally not required or recommended. If detergent is used, surfaces should be rinsed with clean water to remove any residual cleaner, to prevent it from leaving the tile dull and susceptible to more rapid soiling. Usually, water alone is sufficient to clean tile surfaces.

3.3 FIRE AND SMOKE RESISTANCE

Ceramic tile is noncombustible, but when it comes to fires, flames are only part of the potential danger. Toxic emissions of other building materials like plastic and vinyl can include Hydrogen Chloride, Hydrogen Bromide, Hydrogen Cyanide, Carbon Monoxide, and Carbon Dioxide, according to experiments done by TCNA laboratories. Inhalation of these emissions and smoke can lead to impaired mobility, reduced clarity of thinking, incapacitation, and possible death. Unlike plastic materials, tile does not burn, it does not produce smoke in a fire, and it reduces flame spread. These properties make tile an excellent finish system in assembly spaces, egress corridors, and other areas where fire safety is of paramount concern.

3.4 WATERTIGHTNESS

Tile assemblies meeting environmental exposure classification ratings of Com3/Res3 or higher are designed for use in areas that are soaked, saturated, and even submerged. A long history of successful use of tile in showers, tubs, pools, and water features is proof enough that when a tile assembly is carefully specified, designed, and installed using the proper materials, installers, and installation method, the assembly can be made watertight.

3.5 DESIGN VERSATILITY

Tile and tile assemblies are anything but one-size-fits-all. If qualities like extreme durability or watertightness are required, certain specific tiles and assemblies will deliver, but for a backsplash or fireplace surround, or for an art wall or design accent, there are many other appropriate options. Tiles can take the form of tiny mosaics or oversized panels; brightly colored or safely neutral; monochromatic and smooth, or variegated and textured; rectangular, hexagonal, or even round. Used on exteriors as cladding or pavers, on interiors as walls, floors, ceilings, or counters, there is a tile and a method for every application.

3.6 IMPORTANCE OF QUALIFIED INSTALLERS

When discussing the visual and physical characteristics of tile assemblies, it is impossible to discount the contribution of qualified installers. Even with premium materials and proper installation methods, without trained and skilled tile installers, the aesthetics and performance of the assembly can suffer and even fail. Fortunately, the U.S. tile industry has well-established benchmarks to help identify tile contractors and installers with the qualifications necessary to provide durable and long-lasting installations. Contractor certifications like the Tile Contractors' Association of America (TCAA) Trowel of Excellence certification distinguishes best practice tile contractors who are signatory with the International Union of Bricklayers and Allied Craftworker (BAC). The International Masonry Industry Training and Education Foundation (IMTEF) delivers comprehensive tile training for pre-apprentice, apprentice, and journeyworker tile setters and finishers. Installers who hold an Advanced Certifications for Tile Installers (ACT) certification have demonstrated outstanding technical efficiency. Requirements for minimum levels of competence should be written into a project's specifications to ensure appropriate installation.

PART 4: CONCLUSION

Design professionals consider dozens of factors when selecting materials, from the visual attributes of finish materials to the performance characteristics of entire building assemblies. Ceramic tile and the assembly behind it can provide a full spectrum of looks and duties. To aid design professionals in material selection, US standards have clearly defined classifications and designations for aesthetic, physical, and environmental criteria of tile based on science, testing, and performance. In the hands of well-equipped designers and qualified installers, ceramic tile can meet the unique design and performance requirements of any project.