REVIEW OF FACTORS THAT DIRECTLY AFFECT THE DURABILITY OF ADHERED TILE COVERINGS – BRAZILIAN'S SCENARIO INVESTIGATION

Renan P. de Andrade[1], Ana Paula Margarido[2], Julio C. Carvalho[2], Mauricio M. Resende[2], Anderson V. Chaves[3], Flávio L. Maranhão[1]

[1]Polytechnic School of the University of São Paulo – Brazil
[2]Ceramic Center of Brazil – Brazil
[3]ANFACER – Brazilian Association of Manufacturers of Ceramic Tiles, Sanitary Ware and Related Products – Brazil

The high levels of detachment of adhered ceramic tiles throughout Brazil have brought to light the need to resume the discussion on factors that affect the durability of adhered systems. Although these factors have been known to science for a long time through various studies and publications on the subject, the scenario raises the need for them to be remembered so that, consequently, their relevance is evidenced in guaranteeing adherence between the bonds/layers of the ceramic coverings and provide durability. Although when we mention ceramic covering, we often refer to the tile itself, it is important to understand that this element is part of a broader context. An adhered ceramic tile cladding must be seen as a system, as it depends on several elements that work in a closely interconnected way in order to guarantee, in addition to good aesthetic characteristics, good conditions of integrity. These systems are often composed of a base (background), whether of masonry, concrete or light steel framings; anchoring layer (background preparation); rendering layer; adhesive layer, often with the use of adhesive mortar and, finally, the ceramic tile with its grouted joints. Although the layers of the system are exposed to the same weather conditions, these components are made up of materials with different properties and their responses to actions in the application environment are often different since they are adhered to each other.

The response of a given material with certain properties will directly affect the behavior of the adjacent material/layer with different properties that must be adhered. The adhesion of layers composed of materials with different properties causes stress concentrations and a chain response to these demands in the different layers of the system. Computational models, together with experimental programs, have brought important answers to the understanding of these phenomena. When these tensions are added to errors resulting from the project, incorrect specification of the materials used, errors in the execution of each of the layers, non-compliance with current regulations, among other errors that include physical or chemical actions or degradation mechanisms, or even, all these actions added together, can lead to poor accommodation of tensions throughout the covering and directly affect the durability of this adhered system. In regard to this subject, this study seeks to contribute to the understanding of the mechanisms that affect the durability and, particularly, the adhesion in the different layers of the adhered ceramic covering system and, through a bibliographical review, to show which factors directly affect its durability.

1. CONTEXTUALIZATION

According to John and Sato [1] , the analysis of the efficiency of a construction must be done in terms of the degree of satisfaction with which the built product and its systems fulfill the functions for which it was designed. In other words, to the extent to which they meet the needs of their users, guaranteeing minimum durability requirements for a certain period of time. The Brazilian standard on Durability of Residential Buildings [2] defines durability as being assessed by the capacity of the building and its parts to perform their functions under the conditions of use and maintenance during their useful life as stipulated in the project, maintaining the performance of their systems and guaranteeing certain properties of materials. The variation in performance can be represented through a degradation indicator with a measurable characteristic that allows the effects of the degradation processes on the performance of the systems and the materials that constitute them to be monitored.

For Adhered Ceramic Covering Systems (ACCS) for example, tensile adhesion strength is a key property in performance and has its evaluation method prescribed by Brazilian standards NBR 14081-4 [3] and 13755 [4]. The loss of tensile adhesion strength can be used as an indicator of degradation and, therefore, as a major indicator of loss of performance.

ACCS should be seen as a set of closely bonded layers composed of materials with different chemical, thermal and hygroscopic properties. These are multilayer systems made up of a base (background), traditionally made of masonry or concrete; anchoring layer (background preparation); rendering layer (plaster); adhesive layer, commonly made with adhesive mortars or adhesive resins; and a covering layer, made up of ceramic tiles and grouted tiling joints. Therefore, the presence of an interface between these layers is inevitable, but also fundamental for the proper functioning of the system (Figure 1).

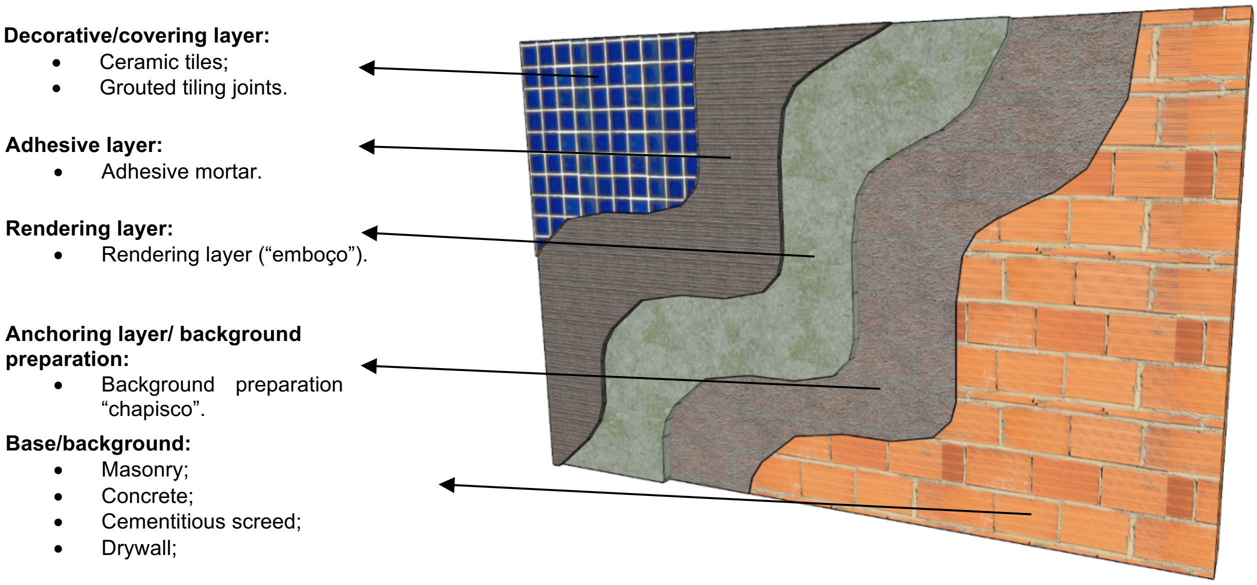

Figure 1 *– Traditional Adhered Ceramic Covering Systems (ACCS) in Brazil.*

Adhesion between ACCS layers can be affected by factors related to the materials used, properties and compatibility of the layers, the application technique used and the climate conditions present at the time the layers are made and the materials are applied, in addition to time and the environmental conditions in which these covering systems will be exposed [5]. As they are intimately adhered, any differential movement in any of these layers will result in the appearance of tensions throughout the adhered assembly (Figure 2). Depending on the characteristics of the materials, geometry and properties of the layers, the stresses arising from these deformations can be of greater or lesser intensity, even resulting in the total loss of adhesion and collapse of the layer's adhesion [6]. The collapse of adhesion at any of the interfaces of the adhered system is known as detachment.

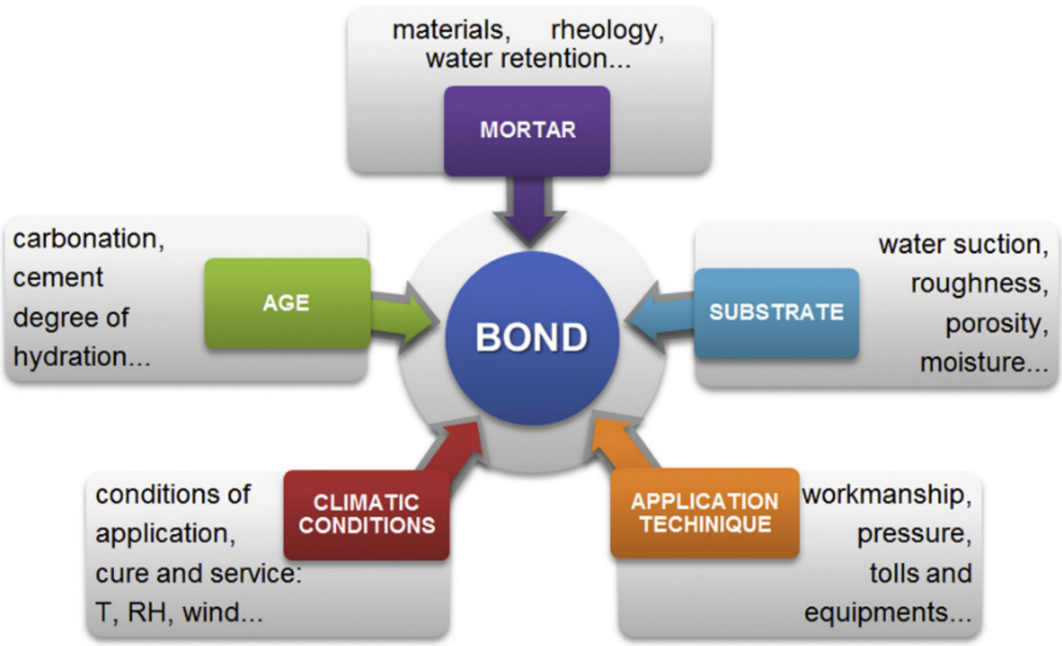

Figure 2 *– Factors affecting ACCS adhesion [5].*

The Brazilian Chamber of the Construction Industry (CBIC) carried out a survey throughout Brazil until 2019 on cases of the pathological manifestation of detachment of adhered ceramic coverings and the verified data includes more than 2.6 million square meters of detached areas, distributed in 157 buildings, 66 cities, 17 states and involves 49 construction companies in the country in addition to 14 suppliers of ceramic tiles [7]. The numbers provided by CBIC present only one scenario related to the sample space surveyed, which leads to reflection on the fact that these numbers are even larger and highlights the magnitude of the detachment pathology faced by the country.

According to the Brazilian Standard for the Durability of Residential Buildings NBR 15575-1 [2], the design useful life of the ceramic covering system must reach at least 20 years for external coverings and facades, and 13 years for internal wall coverings and floor. However, the most common situations of detachment tend to occur less than 5 years after the end of construction [8]. According to these authors, 50.9% of the buildings studied showed pathological signs of detachment on the facades before 5 years of use, a period much shorter than that specified by NBR 15575-1 [2].

The factors that affect the emergence of the pathological manifestation of detachment can be summarized, according to Carasek et al. [5], through the requirements for use and application of the following pillars:

- Mortar
- Substrate
- Application technique
- Climate conditions
- Exposure time (degradation)

2. PILLARS: MORTAR AND SUBSTRATE

2.1 ANCHORING/BACKGROUND PREPARATION MORTAR

The base surface preparation mortar is known in Brazil as “chapisco” (roughcast). Its purpose is to improve the adhesion of the subsequent layer to be executed, ensuring a greater adhesion area through a surface with high roughness and porosity properties [9]. Its primary function is to provide a greater contact area and serve as an adhesion bridge for the execution of the subsequent layer. It has a secondary function of standardizing the surface in terms of water absorption, helping the process of water exchange and retention in addition to mechanical anchoring of the adjacent layer [10]. Generally, its mixture is composed of fine aggregates with a high particle size and a very fluid consistency to guarantee spreadability during the application process. Its rheological properties allow the base mortar to be anchored in the pores of the substrate and the presence of large aggregates provides a greater surface area, allowing greater anchorage of the adjacent layer.

When applied to low permeability surfaces, such as concrete structures and walls, it is important to sand these surfaces to ensure anchoring of the base mortar on the concrete surface.

After sanding, it is recommended to wash the surface so that it is possible to remove loose dust particles that could impede the anchoring process and cause adhesion failure at the interface between the concrete surface and the base preparation mortar.

Negligence in sanding or even washing after sanding has shown cases of detachment of the covering system at this interface, since the concreted surfaces are generally smooth due to the wall effect of the concrete forms, aggravated by the presence of a release agent during the concreting process. The pathological manifestation of detachment can appear during the covering process if these processes are not considered (Figure 3).

Figure 3 *– Pathological manifestation of detachment at the covering interfaces with the concrete surface, even during the execution phase of the adhered covering system.*

Neglecting the curing process of this layer can also cause disaggregation of the aggregates with a significant loss of surface resistance, completely losing the layer's anchoring bridge function. Environments with high temperatures and the presence of strong winds inhibit the cement hydration process and cause the layer to cure incorrectly. Therefore, it is a common reason for adhesion failure and an accelerator of the ACCS degradation process.

2.2 RENDERING MORTAR

It is known in Brazil as "emboço" (render). As defined by the Brazilian Standard for external coverings for facades NBR 13755 [11], the rendering layer has the function of covering and regularizing the surface of the anchoring layer (background preparation mortar), to provide a regular surface/substrate that allows it to receive another layer, such as the decorative mortar covering layer, ceramic covering layer or painting layer.

Its properties are governed by the Brazilian Standard NBR 7200 [12]. As foreseen for the background preparation layer, the rendering layer requires care with the mortar dosage, preparation of the mixture, amount of mixing water, application location, surface preparation, useful life of the mortar, open time and a correct curing process [13].

There are several pathological manifestations associated with incorrect specification of the rendering mortar, incompatibility with the substrate material, correct trace, correct handling, guarantee of the properties specified in the project, surface resistance, etc.

When the rendering layer is applied to external wall coverings and facades, the requirements and precautions are governed by the Brazilian Standard NBR 13755 [9]. When used for internal wall and ceiling coverings, application recommendations and minimum requirements are presented in Brazilian Standards NBR 7200 [12] , 13281 [14], 13749 [15] and 14081 [3,16–18].

2.3 ADHESIVE MORTAR

In the process of laying the ceramic tiles in the ceramic covering layer, the ceramic tiles are adhered using a mortar with adhesive properties. The adhesive mortar is applied with the help of a trowel in which ribbons are formed [9]. The interface between the adhesive mortar and the ceramic tile is often identified as the most critical interface in terms of the risk of adhesion failures [19–21] and, therefore, this process must be carried out respecting several guidelines to guarantee adhesion on the interface. Among these guidelines there are standardized procedures for preparing the substrate, for mixing the mortar, for applying the mortar and slabs, for quantities and recommendations, for the different types of mortar and main slab sizes [4,22,23]. The application technique used and the climate conditions at the time of application are crucial for the good performance and consequent durability of the adhered system.

3. PILLARS: APPLICATION TECHNIQUE AND CLIMATE CONDITIONS

A factor that has a great influence on this pillar is the guarantee of contact area between the adhesive and the ceramic tile. The rheology of the adhesive mortar and the control of the application technique have a great influence on the contact area obtained between the ceramic tile and the adhesive mortar [13,24]. NBR 13755 [9] suggests inspecting the back of the covering after laying as a quality control of the tile laying process. It is not uncommon to find coverage lower than the 90% (Figure 4) required by the Brazilian Standard [25–27], compromising the adhesion strength of the ACCS and consequently its durability (Figure 5).

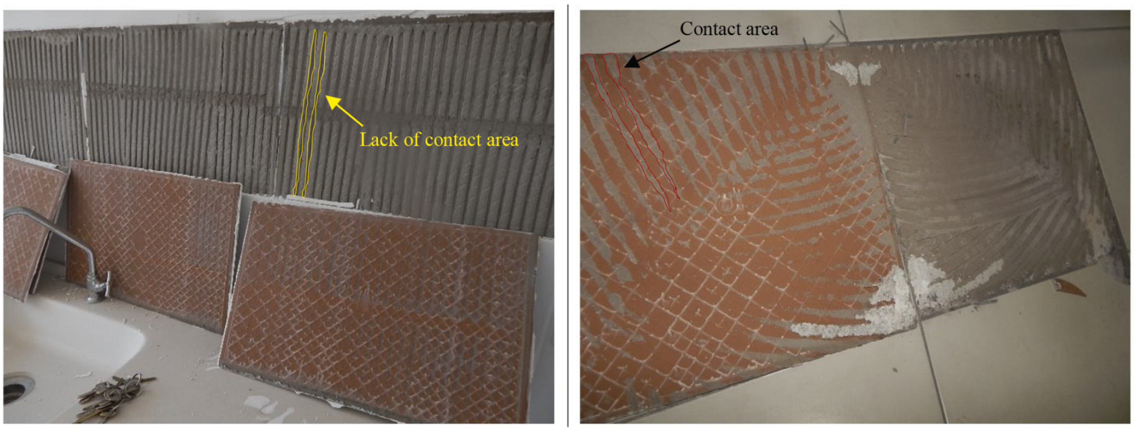

***Figure 4** – Real surface of a detached tile, revealing effective contact area reduction caused by poor setting procedure [27].*

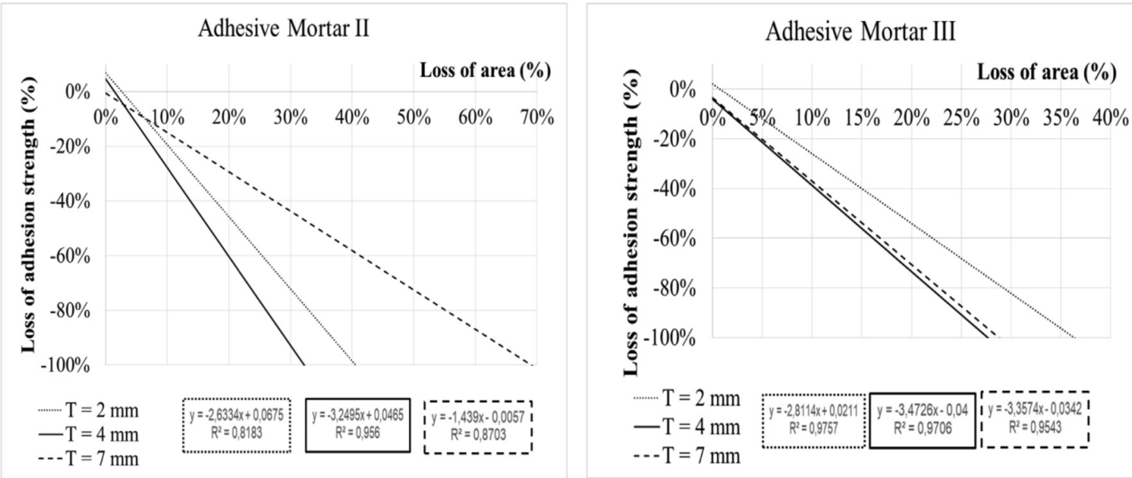

Figure 5 *– Linear trend line of loss of strength due to loss of contact area in specimens with adhesive mortar types 2 and 3 [26].*

In 1992 [28], studies already pointed to neglect in the ceramic tile installation process, in which large areas of adhesive mortar were laid out with subsequent laying of tiles in a sequential manner, with the aim of bringing greater productivity. This inadequate execution sequence causes adhesive mortar open time to expire and is one of the recurring causes of failure of coverings to adhere. The actual open time is the time interval in which the ceramic tile can be laid on the mortar after extending the ribbons. On site, this open time can be checked when, when touching the ribbons, the fingers no longer get dirty with mortar, showing that the open time has been exceeded. It is absolutely essential to apply ceramic tiles while the adhesive is still sticky. If the adhesive dries before installing the ceramic tiles, it may become a plane of weakness as the formation of a surface film on the adhesive mortar ribbon makes it difficult for the adhesive to contact the ceramic tile (Figure 6). This process increases the loss of tensile adhesion resistance (Figure 7) becoming an inducer of future detachment [20].

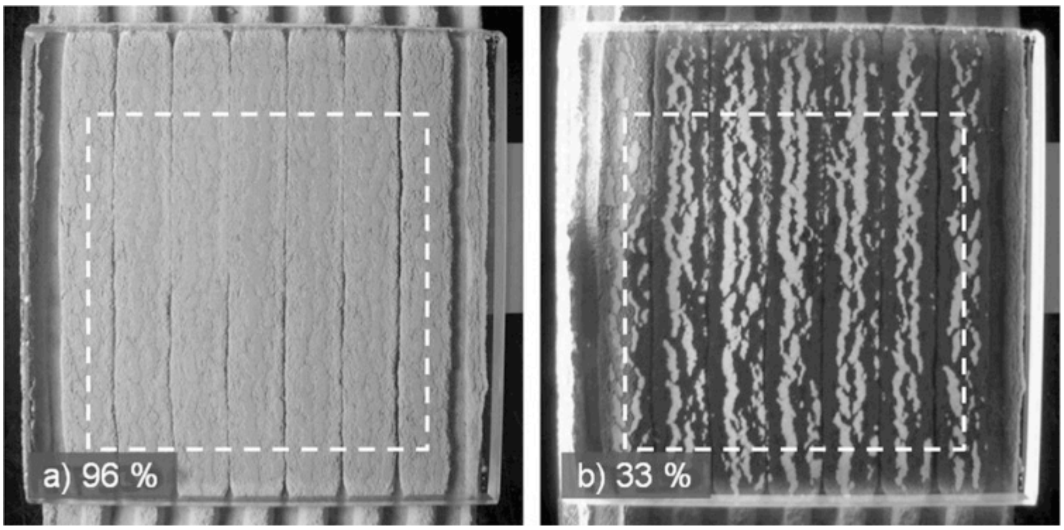

Figure 6 *– (a) Photograph of 10 x 10 cm glass plate embedded 30 min after the mortar was combed. Sample produced according to EN 1347. Mortar ribs are pressed to a degree of 96 area% (measured within the marked area). (b) Same sample illuminated from the side. Skin appears dark. Bright wetting area measures 33 area% (measured within the marked area) [20].*

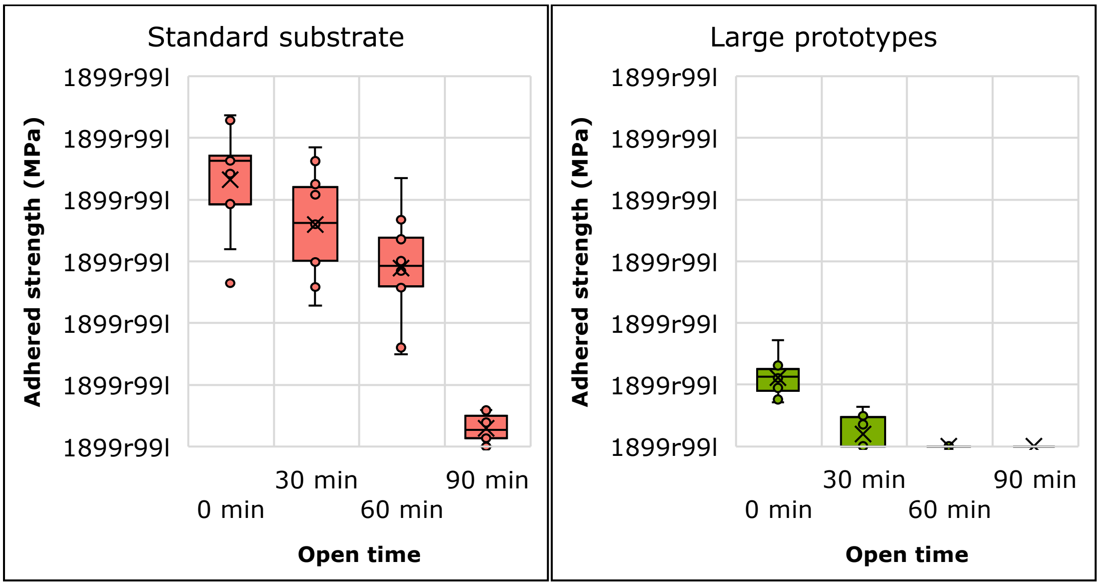

Figure 7 *– Influence of open time on standard substrates and large prototypes with abrupt loss of tensile adhesion strength [29].*

4. PILLAR: EXPOSURE TIME (DEGRADATION)

Several experimental studies have already proven the drop in performance in covering systems when subjected to thermal variations through the propagation of damage. Yiu, Ho and Lo [30] and Andrade et al. [25] measured reductions of more than 50% in shear strength and tensile adhesion, respectively, when subjected to just over 100 cycles of accelerated heating and cooling in laboratory environments.

When exposed to temperature variations, the different layers undergo thermal expansions whose magnitudes depend on their mechanical and thermal properties, such as Young's modulus (E), Poisson's ratio (v) and linear thermal deformation coefficient (α), specific to each material. Restrictions on displacements at the interfaces between the layers, once adhered to each other, together with unequal heating or cooling throughout the thickness of the ACCS, generate differential deformations that, consequently, cause normal and tangential stresses. When the stresses acting on a given layer exceed the resistance limit of the material that composes it, failure occurs. This failure may be restricted to a small region, without practical consequences for the covering, or may propagate throughout thermal cycles [31]. The process of increasing stress peaks is accelerated when there are voids in the bonded interface, accelerating the degradation process. Phenomenon illustrated in several works through computational modeling using finite elements (Figure 8).

In the last two decades, there has been a growing interest in the computational approach for modeling deformations and stresses in these systems [27]. One of the main publications was by Mahaboonpachai et al. [32] which, based on analytical expressions and subsequent analysis of energy and fracture modes at interfaces, is able to show areas with greater concentrations and propagation of damage through mathematical models.

The authors found that the differential expansion between the layers constitutes one of the main factors in the degradation of ACCS, as it accelerates crack propagation and consequently loss of adhesion.

Another important approach was carried out by Felixberger [33] who evaluated the influence of the thickness of the adhesive mortar layer, the dimensions of the ceramic tiles and the mechanical properties of the materials. The author concludes that characteristics such as the position and peaks of greatest shear stresses are generally found at the edges of the coverings.

More recently, several works from the University of Bern have addressed the topic, notably Herwegh et al. [34] who, based on two-dimensional computational numerical modeling, proposed that the deformation imposed by the retraction of the adhesive mortar and the voids left by imperfect bedding are the factors that exert the greatest influence on the decline in performance of ACCS.

Zurbriggen and Herwegh [35] presented maps of stress distribution in covering systems, highlighting that the points with the highest tensile stress are at the edges of the ceramic tiles, confirming the conclusions already found in previous research [33].

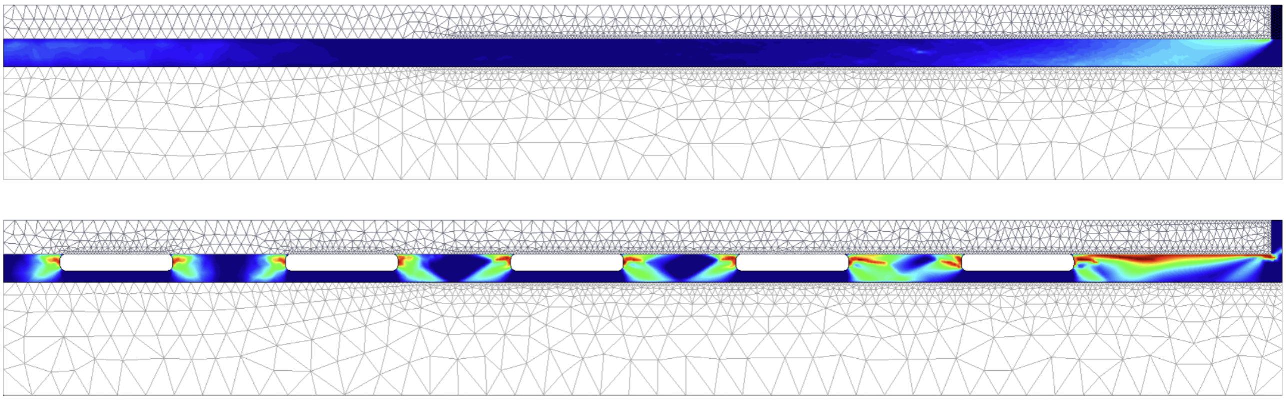

Figure 8 *– Final state of models after heating cycle [31].*

The computational models allowed clear visualization of damage propagation phenomena at interfaces with the presence of voids or bedding faults. Studies proposing large-scale prototyping indicate a substantial reduction in adhesion resistance and abrupt elevation of detached areas, detected by hammer tapping tests in large-scale prototypes [29]. The increase in hollow sound after thermal shock cycles highlights the propagation of damage, as evidenced by computational modeling and the acceleration of ACCS degradation is evident (Figure 9).

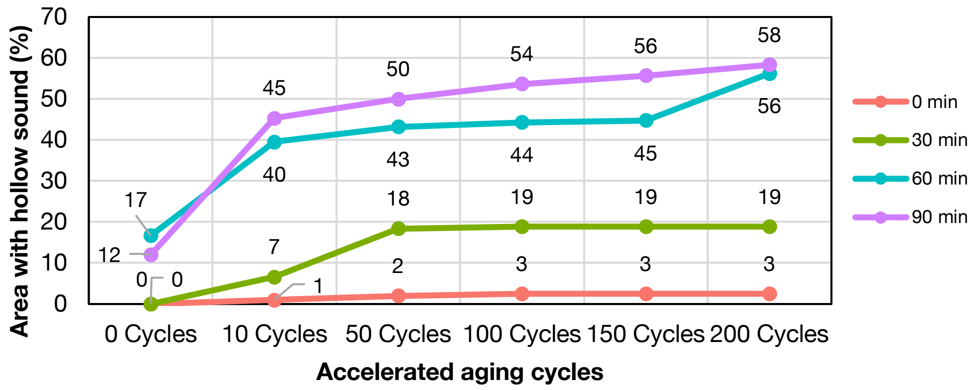

***Figure 9 –** Influence of open time on large prototypes of ceramic covering systems with increased presence of areas with hollow sound (detachment) when subjected to accelerated aging [29].*

5. FINAL CONSIDERATIONS

This work seeks to contribute to the understanding of the mechanisms that affect durability and especially adhesion in the various layers of the adhered ceramic covering system. The high number of cases of covering detachments throughout Brazil have brought to light the need to revisit, through bibliographical review and published discoveries, the factors that affect the durability of bonded systems, even though they are widely known.

The author seeks to present these factors through five pillars: (i) mortar; (ii) substrate; (iii) application technique; (iv) climate conditions and; (v) exposure time (degradation). The main conclusions are presented below:

- Adhered Ceramic Covering Systems (ACCS) must be analyzed and designed as a multilayer assembly and not just as a covering with only aesthetic properties;
- This assembly is made up of layers with different characteristics and properties and its execution must be considered layer by layer;
- Negligence in the execution of any of the layers may cause total collapse of the adjacent layers to which the covering is adhered;
- Various precautions and minimum requirements must be considered regarding the specification of mortars, whether for the anchoring layer, rendering layer or adhesive layer;
- Minimum properties must be guaranteed in the process of executing these layers so that the substrate is able to receive the adjacent layer, guaranteeing good adhesion conditions and promoting durability of the system as a whole;
- The protocols and application techniques prescribed by current standards, good engineering practices and various articles published on the subject must be met;
- The layers of adhered ceramic covering systems must be designed not only to guarantee good performance indicators at the time of execution, but also minimum durability requirements according to their application environment.

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