ANALYSIS OF THE ADHESIVE STRENGTH OF FAÇADE TILING SYSTEMS EXPOSED TO THERMAL CYCLES ON VARYING THE ARRANGEMENT OF THE MORTAR RIBBONS

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1. ABSTRACT

Façade cladding systems (FCSs) play a fundamental role in how buildings perform, as they are responsible for protecting the walls and structures from degrading environmental agents. Consequently, ceramic tiles are widely used, because of their durability and because they are extremely resistant to atmospheric agents such as thermal and hygroscopic variations. However, despite being so widely used, tiles still entail difficulties in their production technology and as a result, numerous examples of pathologies exist. Given such a context, studying a cladding system in order to reduce the number of pathologies is of great value. A ceramic tiling system comprises a set of layers bonded together, and as far as system performance is concerned, the adhesive strength of the bond between the adhesive mortar and the ceramic tile is paramount. Therefore, how the adhesive is applied and the tile bedding are important factors in ensuring the integrity of the ceramic façade cladding system (CFCS) over the years. According to Brazilian standards 13754:1996, 13755:2017 and 14081-2:2015, adhesive mortar must be applied using a notched trowel, so as to provide a layer of regular and uniform thickness on the ceramic tile bedding. Using a notched trowel to spread the adhesive forms ribbons that are subsequently squashed when the tiles are bedded. Very often when installing a CFCS, these ribbons are laid randomly, i.e. not at a standard angle to the ceramic tile. In this sense, the aim of our research is to analyse tensile adhesive strength when ceramic tiles are bedded at two angles (45º and 90º) to the adhesive ribbons after being exposed to a programme of accelerated ageing. To achieve that, BIa-type ceramic tiles measuring 4.8 x 4.8 cm and Type III industrial adhesive mortar were used. Samples were taken according to standard NBR 14081-2:2015 and cured for 28 days. After that, some of the samples were kept at room temperature in the lab for 15 days, while others were subjected to an ageing programme. This hygrothermal cycle comprised the following stages: immersion in water (≅ 20°C) for 4½ hours, 1½ hours at ambient temperature, and 18 hours in an oven (≅ 80°C), thus totalling 24 hours. After 15 cycles, tensile adhesive strength was tested according to NBR 14081-4:2012. The results showed that the angle formed between the ribbons of adhesive mortar and the tiles made no significant difference, while the exposure to accelerated ageing caused a loss of adhesive strength.

2. INTRODUCTION

Ceramic façade cladding systems (CFCSs) are widely used for their durability, aesthetics, wide range of finishes, and easy maintenance [1].

A building's performance and durability are closely related to its behaviour in relation to degrading environmental agents, so façade cladding systems (FCSs) play an important role, since they help to protect and seal walls and structures.

According to Rashed [2], building façades in certain regions can easily reach temperatures of over 50°C, due to direct impact of the sun, so FCSs must have good resistance to heat variations. According to Soares [3], FCSs are the parts most exposed to external weather conditions, such as solar radiation, humidity, temperature, wind, rain, abrasion, impact and rising damp, which lead to a decrease in the service life of the façade cladding.

Reis [1] states that a ceramic façade cladding system (CFCS) is made up of the following layers bonded together: A substrate or base, the adhesive mortar, the ceramic tile, different types of joints and grouting mortar. As Almeida [4] puts it, the layers comprising a cladding system are individually subjected to different strains, which can produce unwanted stresses on the entire unit and eventually the onset of pathological disorders.

According to Silva [5], when a CFCS has a high number of pathologies, such as, for example, tile delamination or detachment, its service life is shortened and so maintenance has to be performed more frequently and, in some cases, tiles recovered or replaced [6].

Several factors are believed to underlie the occurrence of tile detachment, among which the following can be mentioned: workmanship, the design project, execution, the various products used, the building schedule, and other factors such as moisture expansion, thermal expansion and structural movements [7].

In such circumstances, the adhesive mortar layer plays a decisive role in how a ceramic cladding system performs, as it is essential to withstanding the tensile and shear stresses occurring between interfaces [8]. How the adhesive mortar is applied and how the tiles are installed are important factors in guaranteeing the integrity of the ceramic façade cladding system (CFCS) over the years.

According to Brazilian standards ABNTs NBRs 13754:1996 [9], 13755:2017 [10] and 14081-2:2015 [11], the adhesive mortar should be applied using a notched trowel in order to provide a layer of regular and uniform thickness on which the ceramic tiles are placed. Using a notched trowel to spread the adhesive mortar forms ribbons that are subsequently squashed when the tiles are placed, and according to NBR 14081-2 (2015) [11], the ribbons should be arranged longitudinally (at 90º to the tile). However, in practice, sometimes when a CFCS is installed, the ribbons are arranged randomly, i.e. not at a standard angle to the ceramic tiles.

According to a study made by Miebielli [12], in fourteen of the fifteen building sites where a survey was carried out on the use of trowels, the mortar was applied at an angle of between 20º and 45º to vertical.

In view of this situation, the aim of this research was to analyse tensile adhesive strength when ceramic tiles were installed at two angles (45º and 90º) to the adhesive mortar ribbons after the system had been exposed to an accelerated ageing programme, the aim of which was to replicate actual exposure conditions.

3. MATERIALS AND METHODS

Figure 1 provides details of the three main stages (A, B and C) comprising the research.

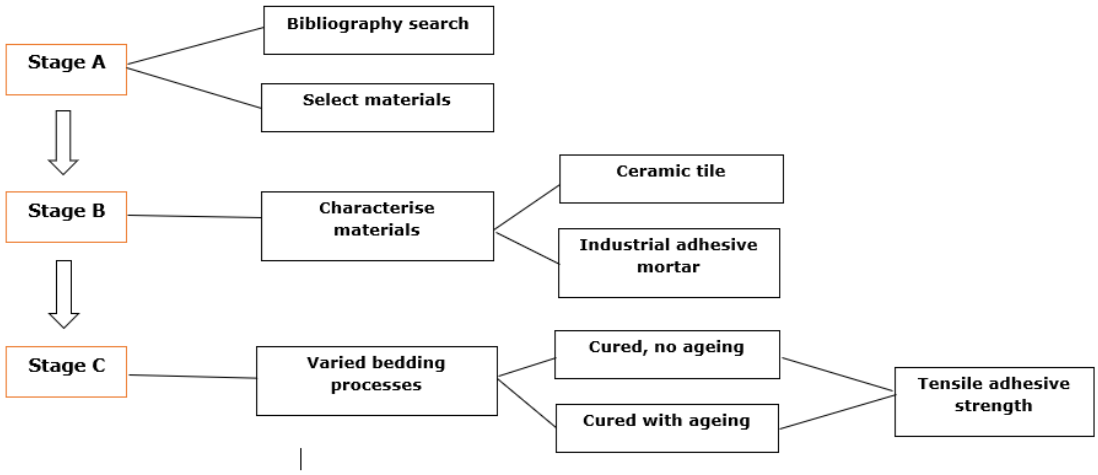


Figure 1. *Diagram of the stages in the research study*

BIa-type, square ceramic tiles measuring 4.8 x 4.8 cm were used according to ABNT NBR 13817:1997 [13], together with Type III adhesive mortar in accordance with NBR 14081-1:2012 [14], standard substrate whose dimensions, composition, water absorption and strength complied with ABNT NBR 14081-2:2015 [11], and a trowel with rectangular notches measuring 5.0 x 5.0 mm, as per ABNT NBR 13755:2017 [10].

To characterise the ceramic tile used, water absorption and moisture expansion tests were performed in accordance with the recommendations of ABNT NBR 13818:1997 [15]. To characterise the adhesive mortar, tests were performed to measure open time, water retention, tensile bending strength, axial compression strength, bulk density in the cured state and tensile adhesive strength, following the respective technical recommendations: ABNT NBR 14081-3:2012 [16], ABNT NBR 13277:2005 [17], ABNT NBR 13279:2005 [18], ABNT NBR 13280:2005 [19] and ABNT NBR 14081-4:2012 [20].

After the materials had been characterised, the test pieces were produced according to the guidelines of ABNT 13755:2017 [10], varying the angles (45º and 90º) to the mortar ribbons.

Figure 2 shows the standard substrates with the laid ceramic tiles, in which the angle of the tile to the ribbons of adhesive mortar varies.

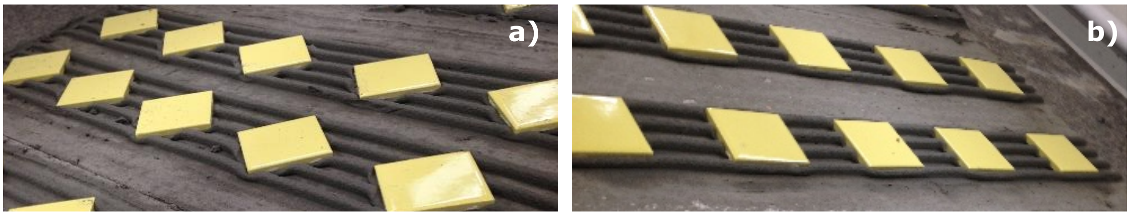


Figure 2. *Difference between angles at which the adhesive mortar is arranged: (a) 45° and (b) 90°*

The samples were all kept for a cure time of 27 days under normal conditions, according to the recommendations of DIN EN 12004-2 (2017) [21] and, following the curing process, 50% of the samples were kept under ambient lab conditions, while the other half were exposed to fifteen hygrothermal cycles.

The cycles performed on the samples included heating in an oven and cooling in a water tank. The hygrothermal cycle comprised the following steps: immersion in water (≅ 20°C) for 4½ hours, 1½ hours at ambient temperature, and 18 hours in an oven (≅ 80°C), totalling exactly 24 hours.

Figure 3 shows the hygrothermal cycle used and Figure 4 the test pieces in the cycle.

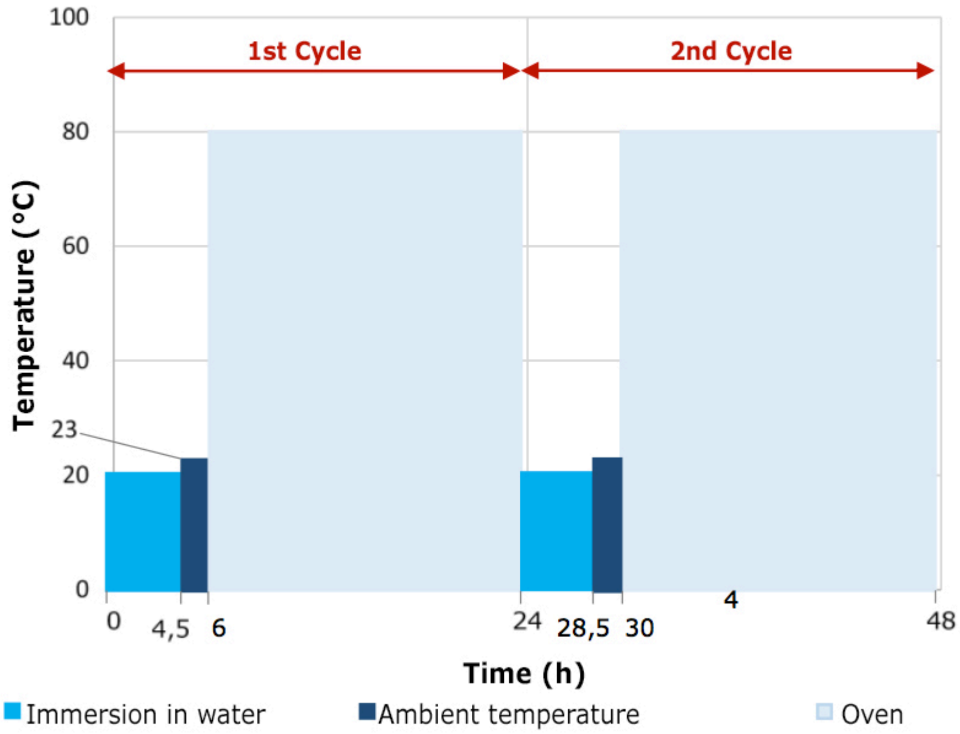


Figure 3. *Graph representing two complete cycles*

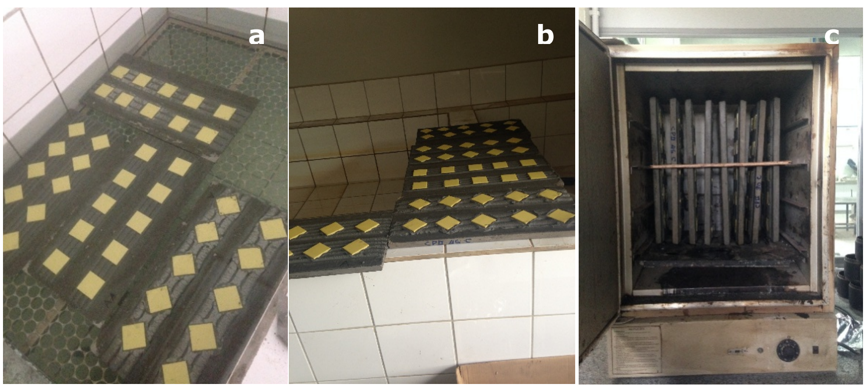


Figure 4. *Cycle process: (a) samples immersed in water, (b) samples at ambient temperature, (c) samples at high temperature*

After the 15 cycles, tensile strength testing was performed to analyse and compare the results.

4. RESULTS AND DISCUSSION

Water absorption in ceramic tiles is a property that allows their porosity and permeability to be related to contact with water. The tiles in our research returned a value of 0.48% with a standard deviation of 0.28%, confirming the manufacturer's specifications. Standard ABNT NBR 13817:1997 [13] suggests a maximum absorption limit of 0.5% for BIa tiles. The moisture expansion results on the tiles used gave an average of 0.48 mm/m, with a standard deviation of 0.11 mm/m, a result that conforms to ABNT NBR 13818:1997 [15], which recommends a maximum limit of 0.6 mm/m.

The results obtained from the characterisation of the industrial adhesive mortar used are shown in Table 1.

Tests	Results	Standard deviation
Water retention	98.99%	…
Open time	0.13 MPa	0.12 MPa
Tensile bending strength	4.56 MPa	0.57 MPa
Axial compression strength	13.55 MPa	0.62 MPa
Bulk density in cured state	1590.97 kg/m^3	17.31 kg/m^3

Table 1. *Properties of the adhesive mortar used.*

Comparing the results obtained against their respective technical standards, the only test that did not produce satisfactory results was open time, bearing in mind that the minimum tensile adhesive strength suggested by ABNT NBR 14081-1:2012 is 1 MPa for Type III adhesive mortars [14].

In the analysis of the results obtained in the tensile strength testing of the samples, the criteria of standard ABNT NBR 14081-4:2012 [4] were used and at the same time, the type of rupture was evaluated.

The types of ruptures are illustrated in Figure 05.

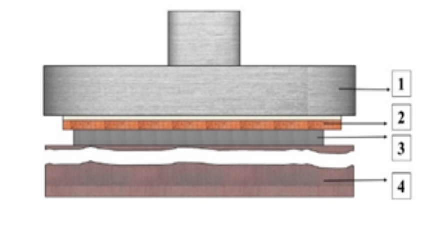
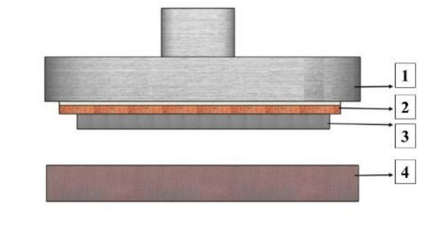
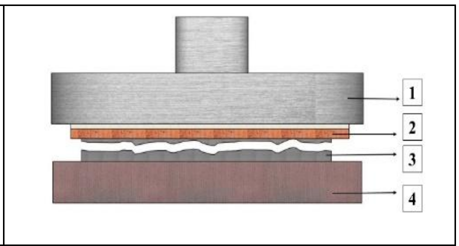
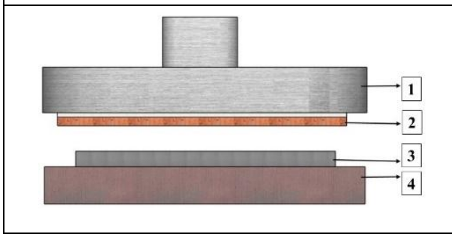
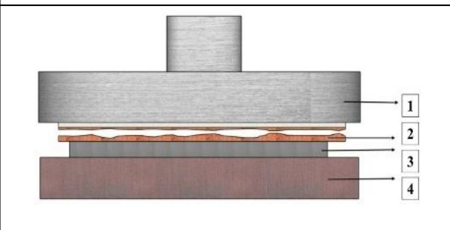
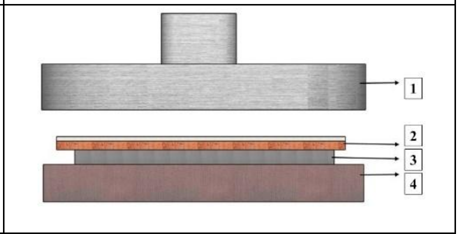
		
Rupture in the substrate –roughcast NBR 14081-4: 2012: S	Rupture in the adhesive mortar and substrate interface NBR 14081-4: 2012: S/A	Rupture in the adhesive mortar NBR 14081-4: 2012: A
		
Rupture in the adhesive and ceramic tile interface NBR 14081-4: 2012: A/P	Rupture in the ceramic tile NBR 14081-4: 2012: P	Rupture in the ceramic tile and metal plate interface NBR 14081-4: 2012: F

Figure 5. *Types of ruptures. Adaptation [8].*
Note: key to numbers: (1) Metal plate; (2) Ceramic tile; (3) Adhesive mortar; (4) Substrate - roughcast.

Tensile adhesive strength results are shown in Table 2. For the results of tensile strength with averages over 0.30 MPa, those that had a deviation of more than 20% from the average were discarded and for results below 0,30 MPa, values that were 0.06 MPa from the average were also discarded, as were samples with rupture types S, P and F (Figure 5).

Samples	Result I		Result II	
	Model / No ageing cycle applied	Standard deviation	After ageing cycle applied	Standard deviation
45º	1.07 MPa	0.18 MPa	0.32 MPa	0.30 MPa
90º	1.06 MPa	0.18 MPa	0.22 MPa	0.30 MPa

Table 2. *Tensile adhesive strength of the samples*

Figure 6 shows the results obtained in the tensile adhesive strength test in graph form for clearer viewing and comparison.

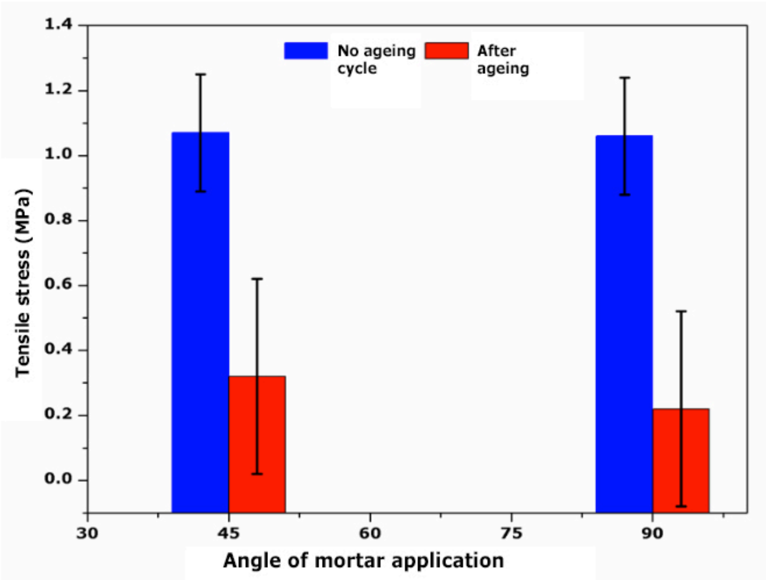


Figure 6. *Average tensile adhesive strength in the samples*

As can be seen from Table 2 and Figure 6, with 95% confidence, no significant difference exists in tensile adhesive strength of cladding systems when the ceramic tiles are bedded at 45º or at 90º to the adhesive mortar ribbons. The bedding angle between the ceramic tiles and the adhesive mortar ribbons did not influence either the reference samples not exposed to the hygrothermal cycles, or the samples exposed to accelerated ageing. This can be explained by the fact that the contact area between the ceramic tile and the adhesive mortar ribbons remained similar and also because both configurations allow for air flushes during the tile laying process, thus eliminating air bubbles between the ceramic tile and the adhesive mortar layer.

However, it is clear that exposing the samples to the hygrothermal cycles was a variable that led to a reduction in tensile adhesive strength in the CFC systems. The samples that were subjected to accelerated ageing decreased their tensile adhesive strength by approximately 75% and 80%, respectively, for the system with the tile at 45º and 90º to the ribbons of adhesive mortar.

According to Wetzel [22], during the life cycle of ceramic cladding systems, it is common for them to gradually suffer a loss of adhesion and thus the link between adhesive strength and system durability is reduced. The main causes for loss of adhesion are the effects of different hygroscopic effects between the layers that make up the ceramic cladding system. Incompatibility between the thermal and humidity expansions in the layers, combined with high thermal variations, can lead to interfacial stresses, which in turn cause detachment [23].

Table 3 shows the types of rupture found in the tensile adhesive strength test, while Figure 7 illustrates the ceramic tiles representing rupture types A/P and S/A.

Samples	Model /No ageing	After ageing
45º	AP and S/A	A/P
90º	AP and S/A	A/P

***Table 3**. Most frequent types of ruptura*

As can be seen in the bedding configuration in Table 3, the angle of the tile to the adhesive mortar ribbons did not influence the most frequently observed type of rupture, and so changing the angle (45º or 90º) is not deemed to make any difference to the results obtained.

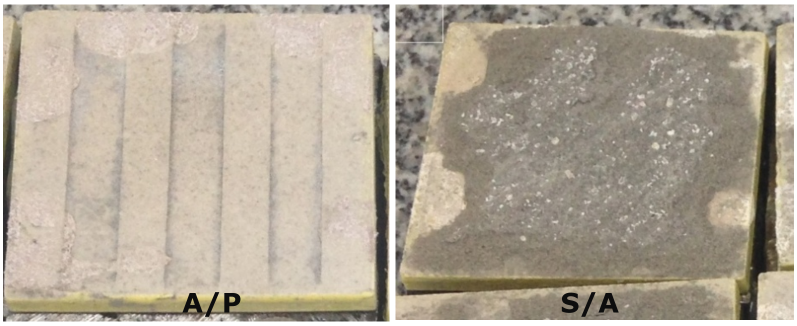


***Figure 7.** A/P and S/A type ruptures*

However, it was confirmed that the ageing cycle interferes with the most frequent type of rupture, i.e., the samples that were not exposed to accelerated ageing cycles displayed more often different ruptures from the samples that were exposed to ageing.

The tiles that were not exposed to ageing revealed frequent ruptures in the adhesive mortar/ceramic tile interface and in the interface between the adhesive mortar and the substrate.

The systems exposed to the fifteen cycles of accelerated ageing emulated older systems and predominantly displayed type A/P ruptures, which refers to unequal movement between the ceramic tile and the adhesive mortar, rather than movements between the adhesive mortar and the substrate. This is due to the fact that the adhesive mortar and the substrate display more similar behaviour patterns as both are cementitious, unlike between the ceramic tile and the adhesive mortar.

5. CONCLUSIONS

The results showed that the angle formed between the adhesive mortar ribbons and the ceramic tiles did not significantly affect tensile strength or the type of rupture. However, exposure to the accelerated ageing process was seen to have an effect, as it caused a loss in tensile adhesive strength in the samples exposed to ageing and altered the most frequent type of rupture observed.

There was no loss of adhesion or change in the type of most frequent rupture when the angle at which the ceramic tiles were bedded on the adhesive mortar ribbons was changed, because the contact area between the mortar and the tile was quite similar and also because both configurations provide for complete adhesion.

The ageing cycles proved to be influential on tensile strength, possibly due to large movements in the systems and the consequent appearance of microcracks that reduce bond strength. The differences in movement between the ceramic tile and the adhesive mortar were more frequent and therefore caused type A/P ruptures more frequently in those systems that had undergone the ageing cycles.

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