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Test Procedure for Evaluating Tensile Bond Strength of Rendering Mortar Applied to Structural Masonry at High Temperatures

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Abstract

In the event of a fire, the detachment of the mortar applied to the substrate compromises the performance of rendered structural masonry walls. The wall surface is often protected by a layer of cement-lime mortar, which helps to delay the temperature rise within the concrete block section. While fire rating tests of masonry walls with rendering mortar have revealed instances of debonding over time, the behavior of rendering mortar at elevated temperatures remains insufficiently understood. A key question is how the high temperatures affect the tensile bond strength of rendering mortar, and there is no standard method that allows obtaining this parameter. The standard method commonly used for room temperature cannot be used for determining tensile bond strength at high temperatures, and a new method must be developed. This study proposes a procedure for determining the tensile bond strength of rendering mortar applied to a concrete masonry substrate when exposed to high temperatures. This information, along with other material properties, is critical for evaluating the fire resistance rating of walls constructed with various material combinations of block and render, and for facilitating numerical modelling of concrete block masonry under elevated temperature conditions. To conduct the investigation, hollow concrete block prisms were manufactured, rendered, and subjected to different test scenarios, varying factors such as the force application mechanism, the sample area and the heating curve. Preliminary results indicate a favorable response in terms of failure mode, and these findings are presented herein. This work may contribute to future research on materials exposed to high temperatures or fire conditions, and the proposed method could be adapted for studies involving different substrates and rendering materials.

Keywords

Fire situation, high temperatures, rendering mortar, structural masonry, tensile bond strength, test procedure.

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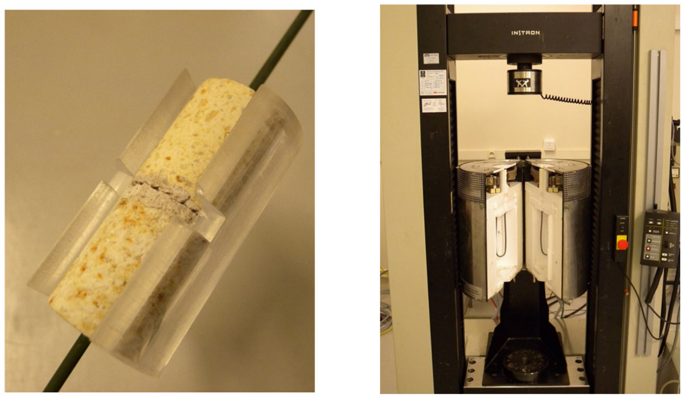
INTRODUCTION

Accidents involving fires in the construction industry are often unavoidable, potentially leading to the loss of life, both due to the fire itself and due to the collapse of the structure resulting from materials strength degradation at high temperatures. In the event of a fire, it is necessary that the structure remains stable until the area is evacuated, with the primary goal being to save lives [1]. In addition to being used as aesthetic finishing for structural masonry walls, the rendering mortar contributes to the fire resistance of walls, both in terms of thermal insulation and even in terms of structural capacity [2]. International regulations on structural masonry in fire situations [3,4] aim to prevent fatalities caused by structural collapse. The European standard EN 1996-1-2 (Eurocode 6) [3] and the American standard ACI 216.1 [4] provide guidelines for determining the Fire Resistance Rating (FRR) considering the influence of rendering on masonry walls. Eurocode 6 defines minimum wall thickness values for different material combinations, load levels, fire resistance rate criteria, for both unrendered walls and walls rendered with a 10-mm thickness. ACI 216.1 [4] presents a procedure for calculating FRR from the block equivalent thickness (block net volume per block height times block length) and considering the contribution of the render thickness on the exposed and on non-exposed faces of the wall. The non-exposed face contribution depends on the rendering material and thickness and is considered by adding a correlated thickness to the block equivalent thickness. The FRR contribution of the hot face is stipulated in terms of "time" (minutes) for specific types of renderings and depending on their thickness, this parameter ensures that the rendering layer will not detach from the substrate during the specified time.

Masonry undergoes a temperature-dependent degradation process, varying across the cross-section. This degradation can ultimately lead to structural failure. The presence of a rendering layer delays the heat flux into the masonry, increasing FRR. This is maintained as long as the rendering layer remains adhered to the substrate. Once the rendering detaches, the heat front advances into the cross-section and FRR decreases significantly. Knowing the temperature on which the rendering layer detaches allows developing models to estimate FRR. Thus, a method for measuring the tensile bond strength degradation of renderings at elevated temperatures, particularly on the fire-exposed surface, will allow more accurate predictions on the behavior rendered masonry under fire situation.

Pull-out tests are commonly used to determine the tensile bond strength of renderings applied to different substrates at room temperature. Several standards provide guidelines for conducting these tests, including EN 1015-12 [5], ASTM D4541 [6] and NBR 15258 [7]. The procedure involves extracting circular 50-mm mortar samples from the rendering's surface, with metallic dollies glued using epoxy, enabling the determination of tensile bond strength upon failure. Various failure modes may occur; however, the expected failure mode is typically the bond between the substrate and the render. Applying this standard test at high temperatures is not feasible due to epoxy's loss of adhesion properties at elevated temperatures. Bueno et al. [8] applied the standard method to evaluate the residual tensile bond strength of plaster rendered to ceramic masonry wall after exposure to high temperature and cooling, but could not test the bond strength at the high temperature. Brulin et al. [9] developed cylindrical specimens glued by a mortar layer, which allowed the bond testing at high temperatures inside a cylindrical-shape kiln (Fig. 1).

There is a lack of studies on the tensile bond strength of rendering mortar at high temperatures, particularly when considering structural masonry exposed to fire. There is no specific method for testing the exposed surface, given the difficulty of performing the tests under elevated temperatures. The objective of this study is to develop a testing procedure that enables the determination of tensile bond strength at high temperatures. The results of various test configurations are presented, considering different pull-out schemes and heating rate curves. The tests were conducted on two-block concrete masonry prisms, rendered on both sides, varying factors such as the force application mechanism, the sample area and the heating curve. Finally, a new preliminary method is proposed. With this method, it would be possible to analyze the adhesion behavior of rendering more precisely and obtain more reliable values for the contribution of the hot face rendering to the FRR of masonry walls.



a) Specimen scheme b) Cylindrical kiln

Figure 1: Cylindrical specimen and kiln for tensile bond test [9].

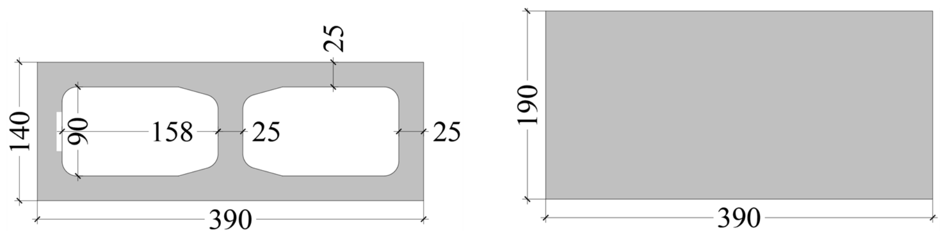
Determining the temperature at which rendering detaches from the substrate allows for the development of numerical models that simulate structural masonry degradation, considering rendering detachment. This approach offers a more cost-effective alternative to large-scale experimental tests. The minimum masonry wall thicknesses provided in Eurocode 6 [3] for various FRRs (with or without the presence of 10 mm of rendering) are applicable to specific masonry configurations in certain regions worldwide. However, when any masonry parameter deviates from standard guidelines, conducting new experimental tests becomes necessary, incurring additional costs. By thoroughly understanding the various factors influencing the tensile bond behavior of renderings applied to masonry, it becomes possible to obtain accurate insights at a lower cost through numerical modelling strategies.

MATERIALS, METHODS AND DISCUSSION

This section outlines the steps and tests involved in developing an procedure for the rendering pull-out test at high temperatures. The materials, accessories and methodologies developed are detailed, followed by a discussion of the results. All the tests were conducted in the Laboratory of Materials and Structures of State University of Campinas (UNICAMP).

Materials

The tests were conducted on rendered concrete block prisms, each consisting of two 6-MPa hollow blocks (compressive strength based on the gross area) laid with a 10-mm mortar joint, also with 6 MPa of compressive strength. The geometry of the blocks is presented in Fig. 2. For rendering, a mortar with a mix ratio of 1:1:6 (cement: lime: sand) was used, with an industrialized roughcast (cement-sand based) for substrate treatment. The choice of using two block prisms is due to the possibility of positioning them at the kiln entrance, as shown in Fig. 3, allowing the bond strength testing at the hot face. This configuration was chosen due to the possibility of testing both hot and cold faces with the same prism, to see the differences between them in future work.



a) Top view   b) Side view

Figure 2: Geometry of concrete blocks.

Figure 3: Prism at kiln's entrance.

Pull-out device

The pull-out standard method [5–7] employs an epoxy adhesive to glue the dollies. The epoxy is unsuitable for high temperatures; thus, an alternative approach must be developed, through mechanical adhesion (instead of bond adhesion). Several preliminary tests were conducted using different materials and connection methods to determine the most suitable device for pulling the samples out under high temperatures. The first approach involved embedding a glass fiber mesh within the mortar layer during application. However, this method did not produce the desired failure mode due to the flexibility of the glass fiber. The second approach utilized steel wires, also embedded within the mortar during application. When the pull-out force was applied, the wires tended to cut through the mortar internally, with failure due to the shear of mortar layer. In the third approach, a hooked pin with a welded 20-mm diameter washer was developed, demonstrating the most favorable performance among the three tested methods.

The subsequent tests were performed using the hooked pins (Fig. 4a), with the objective of positioning the pin at the substrate's surface before applying the roughcast and rendering mortar and pulling the samples out after complete curing of rendering. Four such pins were lightly glued to the block substrate (Fig. 4b), at the exposed face of each prism using instant glue, which has a melting point between 100 °C and 150 °C, ensuring minimal influence on the test results under high temperatures. Once the pins were attached, the industrialized roughcast was applied to both faces, and then the rendering mortar with a thickness of 10 mm. The final look of the prisms is shown in Fig. 4c. The limitation of four tests per prism is due to the proximity of the extraction points. Increasing the number of extraction points would reduce the available space between them, potentially causing interference and influencing the results of adjacent tests. To evaluate the behavior of the testing setup, different methodologies were tested, considering the load application mode, the load intensity, and the presence or absence of circular openings around the pull-out pins. The details of each attempted test procedure are described in the next section.

a) Pull-out pin　　b) Pins fixed on the prism　　c) Prism after rendering

Figure 4: Rendered prism with pull-out pins.

Pull-out area

After the render curing for 28 days, two different pull-out areas were considered. One option was to consider pulling a small circular area cut-isolated around each pin. Another option was to pull the four pins at the same time, considering the full-face area. The different try-configurations of the tests are summarized in Table 1, in addition to the insights from each test. The main idea is to pull the same area at room temperature and at high temperatures, to obtain degraded tensile bond strength relative to the original, before heating application. All the tests were performed using the 20-mm diameter pin presented in the previous section. A total of four prisms were tested with different methodologies, and then the last attempt was replicated in a fifth prism to obtain enough results for the statistical comparison analysis.

The initial attempt to cut around the pins using a 53-mm diameter hole saw was unsuccessful, as the samples detached under the torsional force applied by the drill. The possible cause is that due to the presence of the pins, the bonding area is reduced and the torsional capacity during the cut is not enough.

Table 1: Summary of testing methodology attempts.

Attempt	Methodology	Test temperature	Test insight
1	Cutting openings with a 53 mm diameter hole saw	** Test was not possible	The samples were too small to the pin diameter, with premature detaching
2	Without cutting openings	Increasing heating following ISO 834-1 [10]	Irregular failure mode, with a tendency of failure due to shear stress on rendering layer cross-section
3	Cutting openings with a 100-mm diameter hole saw	Room temperature	Irregular failure mode, with a tendency of failure due to shear stress on rendering layer cross-section, even with openings around the pins
4	Cutting openings with a 70-mm diameter hole saw	Room temperature	Acceptable failure mode, with a tendency of failure in adhesion between rendering and block

The second attempt involved testing without cutting openings around the pins, pulling the four points with a steady weight during the surface heating process, with the expectation that the entire rendering would detach when it reached the critical temperature at the interface, at the specific pulling load. The prism was positioned at the kiln entrance, which had the same 400 mm × 400 mm rendered surface dimension of the prism. The external surface is exposed to room temperature (not directed subjected to heating) and the surface containing the pins is exposed to the heating inside the kiln. A steel cable was attached to the pin hook and passed through holes located at the rear of the kiln. The cable's end, once outside the kiln, was routed through pulleys attached to a metal trestle, with 1-kg weight suspended from the cable and connected to each pin, as shown in Fig. 5a. The weights remained attached to the pins throughout the heating process, until detachment occurred. The failure mode resulting from this test is shown in Fig. 5b. Instead of the rendering completely detaching, each of the pins came loose at different temperatures, with some failures occurring due to shear stress on the rendering layer cross-section, showing a tendency for the render to be divided into four parts. This try-test highlighted the need to delimit the pulling area. This test, if successful, would allow determining the maximum temperature that a specific bond strength would hold.

In the subsequent test, circular openings were created using a hole saw with a diameter of 100 mm. This larger diameter facilitated the cutting process, preventing premature detachment of the sample. At this point, it was decided to conduct the following tests at room temperature, until a definitive testing method was possible to be replicated under high temperatures. A setup like the previous test was used, but with the pull-out force gradually increasing until failure, instead of fixing an initial load. The increasing load was applied by filling a metallic container attached to the cable's end with small steel disks, with scheme shown in Fig. 5c. Fig. 6 illustrates the two samples before testing and failure mode after testing, showing that, rather than pulling the samples out, the failure was due to the mortar layer punching shear failure. This indicated that the 100-mm hole saw was too large for the pin head area.

In the fourth attempt, a hole saw with a diameter of 70 mm was used to cut the openings around the pins. This method successfully allowed the mortar to be cut without compromising the integrity of the sample, as shown in Fig. 7a. Pull-out tests were conducted at room temperature similarly to third attempt. The samples were pulled out as expected, with the fracture occurring between the mortar and the roughcast layer, as illustrated in Figs. 7b and 7c. Therefore, the sample cut using the 70-mm hole-saw prevented premature detachment and ensured that the failure mode occurred within a measurable area. This method was repeated for a fifth attempt to obtain additional results and to allow statistical analysis.

a) Test scheme – fixed load b) Failure mode c) Test scheme – increasing load

Figure 1: Test schemes and failure mode.

a) 100 mm samples

b) Failure mode

Figure 2: Samples and failure mode for 100 mm diameter.

a) 70-mm samples

b) Failure mode #1

c) Failure mode #2

Figure 3: Samples and failure mode for 70 mm diameter.

Proposed pull-out procedure results compared to regular pull-out procedure results

The standard dolly-type pull-out tests [5–7] were also conducted at the same prisms where the proposed pin-type pull-out tests were conducted. Two prisms were used in the tests (prism from fourth attempt and another with replicated methodology), and four pull-out points for each prism and each test methodology. The extraction points corresponding to each pull-out type are illustrated in Fig. 4. This allowed the evaluation of potential differences between both methods. The Positest AT-M device was used for the standard tests. The blue circles indicate the positions for the standard method, while the red circles denote the positions for the proposed method. The results are presented in Table 2. A noticeable difference was observed between the results of the two methods. A one-way ANOVA analysis confirmed a statistically significant difference at the 0.05 level, with a p-value of 2.31×10^{-6}, indicating a very low probability of identical results between the two methods. Fig. 5 depicts the distribution of tensile bond strength results for each pull-out method. This difference can be attributed to variations in stress distribution, as shown in Fig. 6. In the standard method, the force is applied to the full external surface of the saw-cut rendering. In the proposed method, the force is applied at the interface between the render and the block, loading a smaller area equal to the pin head area. This creates greater stress concentration due to the internal compression of the rendering layer. Although the adapted method yielded different (lower) results than the standard, it remains a viable approach to testing at high temperatures. When studying the tensile bond strength at high temperatures, it is essential to perform tests at room temperature first, as these results serve as a reference for subsequent heating tests. In this study the pin-type test yielded average results equal to 32% of the dolly-type test.

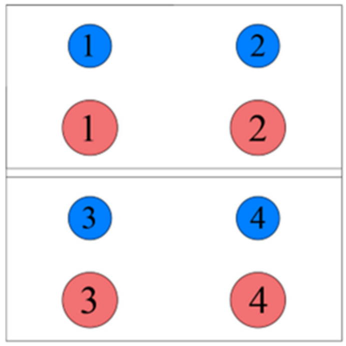


Figure 4: Pull-out samples position.

Table 2: Tensile bond strength results for both pull-out methods.

Prism	**#**	**Proposed - Pin**	**Standard - Positest**
		Bond Strength (MPa)	**Bond Strength (MPa)**
1	1	0.18	0.45
	2	0.12	0.45
	3	-	0.53
	4	0.11	0.67*
2	1	0.11	0.35
	2	0.18	0.58
	3	0.14	0.52**
	4	0.17	0.15**
Mean		0.15	0.45
Lower limit [7]		0.10	0.31
Upper limit [7]		0.19	0.58
Recalc. Mean		**0.15**	**0.47**
SDV		0.03	0.09
COV		22.10%	18.69%

* Rupture between epoxy and mortar – value excluded from mean.

** Values above or below the ± 30% limit [7].

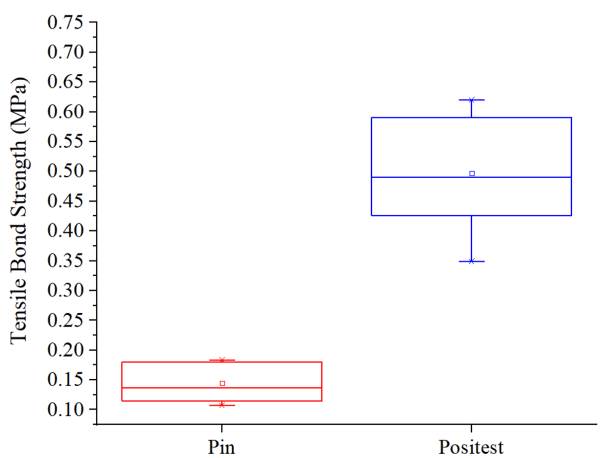
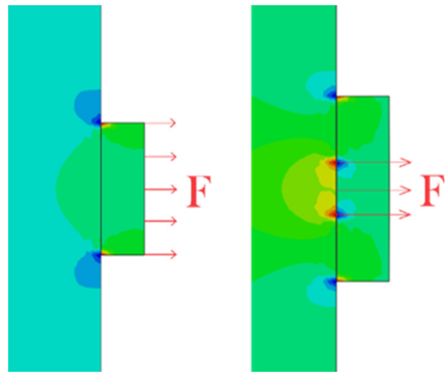


Figure 5: Distribution of tensile bond strength values for both methods.



a) Standard b) Proposed

Figure 6: Stress concentration for each test method.

Time-need for a steady temperature in the interface

The subsequent analysis included numerical simulations to determine an appropriate heating process for conducting pull-out tests at high temperatures. During the second attempt, it was observed that the temperature at the hot interface increased rapidly, following the standard fire curve [10]. This significant variation was deemed unsuitable for testing. Each pull-out point is tested subsequently, with a few minutes gap between each test. There must be no significant temperature difference in the interface during the time needed to test all points. In other words, the temperature at the interface must be steady during all the pull-out testing.

The interface temperature between block and render (point of interest) is not the same as the kiln temperature. It takes some time for the interface temperature to get close to the kiln temperature, and it will not be the same unless an extended time is awaited. It is necessary to determine how long to wait before the interface-surface temperature is steady and close to the kiln temperature.

To address this issue, numerical models were utilized to calibrate a more suitable heating curve and streamline the analysis process. The details of modelling concrete hollow masonry at high temperatures using Abaqus software are outlined in previous studies [11,12].

A try heating curve with a controlled rate of 4 °C/min, the maximum rated allowed at [13] (preventing premature cracking due to abrupt temperature increase), and a maximum temperature plateau of 200 °C were adopted, as a possible testing temperature (blue line). From Fig. 7, considering the 10-mm rendering (red line), it is possible to observe that between 120 and 150 minutes the render/block interface temperature variation is less than 5 °C, allowing enough testing time without significant variation. For the 20-mm render (black line), it would be necessary to wait 150 minutes before reasonable steady temperature (less than 5 °C difference) is reached. When performing the pull-out test, the interface temperature must be recorded and will be lower than the kiln temperature.

Despite the lower actual temperature at the interface, it is still possible to determine tensile bond strengths at various temperatures in the render/block interface. This enables the development of curves depicting interface tensile bond strength as a function of temperature. For experimental tests, thermal couples must be positioned at the render/block interface to register the actual temperature when the samples are tested and guarantee the temperature uniformity between all pull-out samples. The analysis of bond strength versus temperature provides valuable insights into the adhesion performance of rendering mortar under elevated temperatures, as might occur during a fire. With this understanding, it becomes possible to predict the duration that rendering mortar can protect the structural masonry wall in a fire situation.

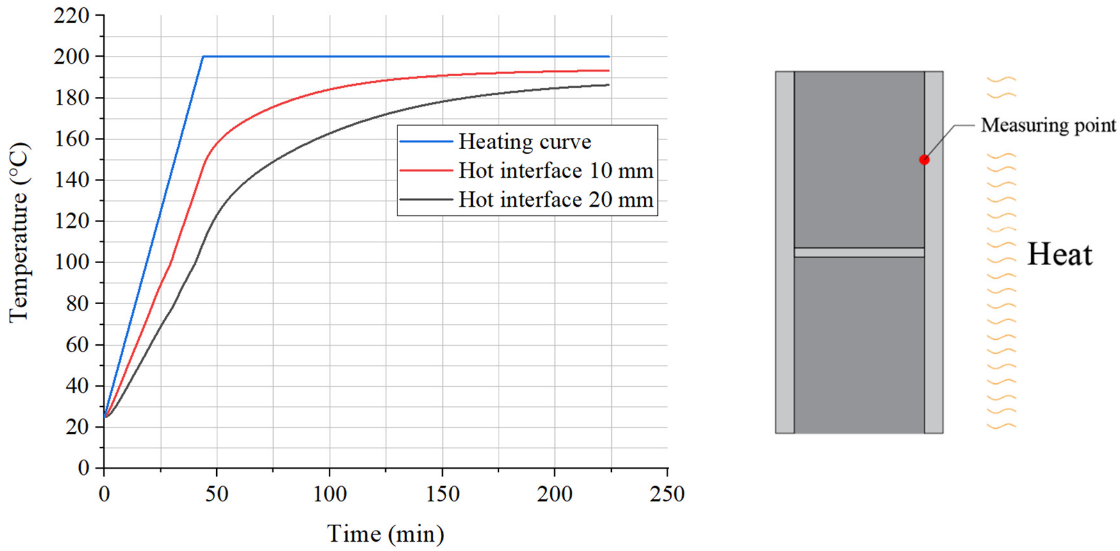


Figure 7: Heating curve and hot interface behavior for 10 and 20 mm of rendering.

The summarized step-by-step protocol to facilitate the replication of the proposed method is presented in Fig. 8.

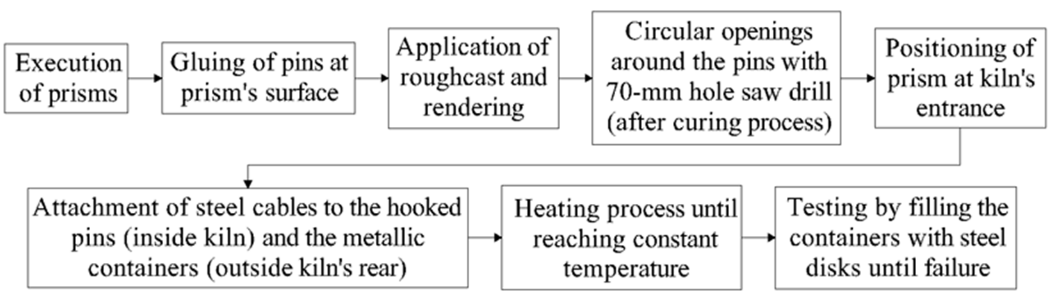


Figure 8: Step-by-step protocol for conducting the proposed test.

CONCLUSIONS

This study focused on the development of a procedure for testing tensile bond strength of rendering applied to structural masonry exposed to high temperatures.

The use of a pin welded to a washer-head proved to be an effective alternative to the standard dollies typically used for tensile bond strength tests. The high temperature deteriorates the glue used to fix standard pull-out dollies, preventing this test-type application.

The preliminary ANOVA analysis conducted on the results from the proposed and standard methods confirmed statistical differences between them due to variations in stress concentration. The sample size for this analysis was limited, and future research should include additional tests with various material combinations to enhance the reliability of the proposed method.

Considering the maximum temperature of 200 °C, the tests should be performed after 120 minutes of heating for 10 mm of rendering and after 150 minutes of heating for 20 mm of rendering, ensuring a maximum temperature variation of 5 °C between all the four samples that will be tested.

With the proposed method, it is possible to determine the rendering mortar tensile bond strength at different temperatures and to evaluate its degradation as temperature increases. It is important to note that, due to the differences between the proposed method and the standard method (particularly regarding stress concentration), analyzing tensile bond behavior at high temperatures using the proposed approach requires testing samples at room temperature to establish a reference for subsequent analysis.

This methodology can be adapted for various scenarios, considering different rendering materials and substrate types. The results can contribute to deriving a rationale for specifying the rendering layer as an effective protection during a fire.

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