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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final report dated 6/Apr/2023

Feasibility of aerogel insulation render systems

Machbarkeit von Aerogel Hochleistungdämmputz-systemen

Source: ©Dr. Daniel Sanz Pont 2021

Date: 6 April 2023

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Co-financing:

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SFOE contract number: SI/502237-01

Zusammenfassung

Aerogel-Dämmputze haben im Gegensatz zu Aerogel-Platten/Decken noch nicht ihr volles Potenzial in Bezug auf die Wärmedämmleistung erreicht. In diesem Sinne ist die Wärmeleitfähigkeit von Aerogelputz (λ>28mW/m-K) mehr als doppelt so hoch wie die des verwendeten Aerogelgranulats (λ=13 mW/m-K). Dennoch könnte Aerogelputz im Vergleich zu Aerogelplatten ein wesentlich besseres Kosten-Nutzen-Verhältnis bieten, da die Kosten für das Granulat im Vergleich zu letzteren um 60 % niedriger sind. Darüber hinaus werden auch die Installationskosten als niedriger eingeschätzt, was das Potenzial beweist, die Gesamtkosten für Renovierungen um mehr als 25 % zu senken, was auch gegenüber dem Massenmarkt wettbewerbsfähig ist. Allerdings gibt es auf verschiedenen Ebenen Hindernisse für die Erzielung von Hochleistungsputzen, insbesondere in Bezug auf die Anwendung, Robustheit und strukturelle Stabilität des konstruktiven Systems. Darüber hinaus ist die Marketingstrategie für Wärmedämmung im Allgemeinen nicht vorteilhaft für Aerogelprodukte, da sie den Wettbewerbsvorteil von Aerogellösungen im Vergleich zu herkömmlichen Materialien nicht wirtschaftlich darstellt. Insbesondere die Kosteneinsparungen bei der menschlichen Arbeit sind nicht gut verstanden, was eine tiefgreifende Analyse der endgültigen Renovierungskosten unter Verwendung verschiedener Produkttypen erfordert.

Dieses Projekt bietet Lösungen, um die oben erwähnten Hindernisse zu überwinden. Insbesondere aus technischer Sicht bringt dieses Projekt eine technologische Innovation, um während der Anwendung die Robustheit von Aerogel-Dämmputzen mit geringen mechanischen Eigenschaften auf der Basis von mineralischen Bindemitteln zu verbessern. In diesem Sinne demonstriert das Projekt die Innovation durch die Anwendung eines verbesserten WDVS-Systems auf der Grundlage eines neuen Hochleistungs-Aerogelputzes bei der Renovierung einer 40 m^2 großen Fassade einer Villa in Lenzerheide.

Zusätzlich wurde eine modulare Konstruktion mit Testplatten mit dem gleichen Fassadenaufbau gebaut, um die Studie durchzuführen. In diesem Sinne bestand die Methodik aus einjährigen Dauerhaftigkeits- und physikalischen Tests für zwei Arten von mineralischen Aerogel-Putzen, die den Vergleich verschiedener Aspekte der Materialeigenschaften ermöglichten. Die Ergebnisse zeigen, dass das neue vorgeschlagene Fassadensystem eine erhebliche Verbesserung der mechanischen Stabilität und der langfristigen Haltbarkeit bietet.

Insbesondere wurden zwei wichtige innovative Aspekte untersucht und erreicht. Einerseits wurde festgestellt, dass die Anwendung einer Tiefengrundierung auf dem Substrat eine bessere Aushärtung des mineralischen Bindemittels fördert und somit die mechanischen Eigenschaften insgesamt verbessert. Es hat sich gezeigt, dass Substrate einen großen Einfluss auf die Stabilität des Putzes haben können, da sie nach dem Auftragen des Putzes Wasser binden. Wie in diesem Projekt gezeigt wurde, kann dieser Effekt durch die Anwendung von Silan-/Siloxan-Hydrophobierungsmitteln auf dem Substrat kontrolliert werden. Durch die Oberflächenbehandlung wird der Hydratationsgrad der mineralischen Matrix erhöht, wodurch die mechanischen Eigenschaften bis zu einem gewissen Grad verbessert werden.

Darüber hinaus hat sich gezeigt, dass die Lösung auf eine breite Palette von Substraten wie Beton, Tonziegel, Kalksandstein und Naturstein aufgetragen werden kann, wobei in allen Fällen eine teilweise Hydrophobierung der Oberfläche erreicht wird. Auf der anderen Seite bietet dieses Projekt auf Systemebene eine Konfiguration des WDVS, die zusätzlich zur Oberflächenbehandlung der Oberfläche die Einbeziehung mechanischer Befestigungen am schützenden Klebemörtel/Einbettungsnetz vorsieht, wodurch die Robustheit und langfristige Haltbarkeit des konstruktiven Systems weiter verbessert wird.

Unter dem Gesichtspunkt der kommerziellen und wirtschaftlichen Durchführbarkeit ermöglicht dieses Projekt ein besseres Verständnis der Sanierungskosten von traditionellen und Aerogel-Lösungen, basierend auf der Analyse jedes Aspekts der Sanierung, wodurch eine realistischere Kostenkalkulation möglich wird. Insbesondere wurde festgestellt, dass durch die Verwendung von Hochleistungs-Aerogel-Dämmstoffen (λ>20mW/m-K) und noch mehr Aerogel-Putzen die Arbeitskosten gesenkt werden können

(besonders teuer in der Schweiz). Die Ergebnisse der Analyse zeigen, dass unter Berücksichtigung aller Kosten einer Renovierung, einschließlich der Aspekte, die typischerweise in den Renovierungsbudgets nicht berücksichtigt werden, wie z. B. die Überarbeitung von Fassadendetails, Fensterleibungen und An- und Abschlüsse, die Kosten für die Verwendung herkömmlicher Dämmstoffe oft viel höher sind als erwartet.

Die höhere Leistung von Aerogel-Produkten und noch leistungsfähigeren Aerogel-Produkten ermöglicht jedoch eine erhebliche Senkung dieser Kosten, so dass die endgültigen Renovierungskosten viel wettbewerbsfähiger sind. Das Erreichen höherer Dämmstandards kann sogar ohne tiefgreifende Fassadensanierungen mit Aerogel erreicht werden, was den Vorteil hat, dass man Zuschüsse von der Bundesverwaltung erhält. Im Rahmen dieses Projekts wurde ein kostenloses Online-Tool für eine Kostenschätzung und potenzielle Einsparungen entwickelt, das realistische Berechnungen für Renovierungen mit herkömmlicher und Aerogel-Dämmung liefert und zeigt, dass die Aerogel-Dämmung wettbewerbsfähiger ist als erwartet. Das Tool hat das Potenzial, die Marktdynamik der Aerogel-Dämmung zu verbessern, um eine bessere Marktdurchdringung dieser Art von Produkten zu erreichen, und es wird erwartet, dass es aktiv zur Förderung der Aerogel-Dämmung eingesetzt wird. Das größte Potenzial kann jedoch mit Hochleistungs-Aerogelputz in Bezug auf die Gesamtkosten erzielt werden, der somit wirtschaftlich besser realisierbar ist.

Die Umsetzung der Erkenntnisse aus diesem Projekt erfolgt schließlich durch die kurzfristige Markteinführung eines Hochleistungs-Aerogelputzes durch die Aeroskin Tech AG und den Vertrieb dieses Aerogelputzes durch die Agitec AG. Darüber hinaus wird die kostenlose Online-Plattform von der Agitec AG für die Vermarktung des Aeroskin Tech-Aerogelputzes, aber auch für ihre breite Palette an Aerogel-Produkten und Fassadensystemen umfassend genutzt werden.

Eine weitere Umsetzung der Ergebnisse hat bereits stattgefunden, und zwar durch die Einführung von Tiefengrundierungen in Fassadensystemen und deren Auswirkung auf die Wasseraufnahmefähigkeit von Baumaterialien, insbesondere von solchen, die in Gebäudefassaden verwendet werden. Das Wissen wurde bereits teilweise im letzten Herbstsemester in der Lehrveranstaltung "Bauphysik" für Bauingenieure des Instituts für Baustoffe am D-BAUG - ETH Zürich umgesetzt. Dennoch werden weitere Konzepte, insbesondere im Zusammenhang mit Aerogel-Dämmsystemen, im Laufe dieses und im nächsten Jahr angewandt werden.

Die nächsten Schritte aus technologischer Sicht sollten sich auf die Verbesserung des Gesamtverhältnisses zwischen mechanischen Eigenschaften und Wärmedämmung konzentrieren, um die Wärmeleitfähigkeit von Aerogelputz weiter zu reduzieren. Es hat sich nämlich gezeigt, dass die Gesamtkosten umso stärker gesenkt werden können, je geringer die Wärmedämmkapazität eines Aerogelputzes ist. Aus kommerzieller Sicht dürfte die weit verbreitete Nutzung und Validierung des bereitgestellten Online-Tools die Marktakzeptanz von Aerogelprodukten und insbesondere von Hochleistungs-Aerogelputzen mit höherem Marktpotenzial verbessern.

Résumé

Les enduits isolants en aérogel, contrairement aux panneaux/blanchisseries en aérogel, n'ont pas encore atteint leur plein potentiel en termes de performances d'isolation thermique. En ce sens, la conductivité thermique des enduits aérogel (λ>28mW/m-K) est plus de deux fois supérieure à celle des granulés aérogel utilisés (λ=13 mW/m-K). Néanmoins, les enduits aérogels pourraient offrir un bien meilleur rapport coût/bénéfice que les panneaux aérogels, car le coût des granulés est 60 % inférieur à celui des panneaux aérogels. En outre, les coûts d'installation sont également estimés plus faibles, ce qui prouve le potentiel de réduction des coûts globaux de rénovation de plus de 25 %, tout en étant compétitif par rapport au marché de masse. Cependant, les obstacles à la réalisation d'enduits à haute performance existent à différents niveaux, notamment en ce qui concerne l'application, la robustesse et la stabilité structurelle du système constructif. En outre, la stratégie de commercialisation de l'isolation thermique en général n'est pas favorable aux produits aérogels, car elle ne démontre pas économiquement l'avantage concurrentiel des solutions aérogels par rapport aux matériaux traditionnels. En particulier, les économies réalisées sur les coûts de main d'œuvre ne sont pas bien comprises, ce qui nécessite une analyse approfondie des coûts de rénovation finaux en utilisant différents types de produits.

Ce projet propose des solutions pour surmonter les obstacles susmentionnés. En particulier, d'un point de vue technique, ce projet apporte une innovation technologique pour améliorer, lors de l'application, la robustesse des enduits isolants aérogels à faibles propriétés mécaniques basés sur des liants minéraux. En ce sens, le projet démontre l'innovation par l'application d'un système ETICS amélioré basé sur un nouvel enduit aérogel haute performance dans le cadre de la rénovation de la façade de $40m^2$ d'une villa à Lenzerheide.

En outre, une construction modulaire avec des plaques d'essai avec la même configuration de façade a été construite pour réaliser l'étude. En ce sens, la méthodologie a consisté en des tests de durabilité et des tests physiques pendant un an pour deux types d'enduits minéraux à base d'aérogel, ce qui a permis de comparer différents aspects des propriétés du matériau. Les résultats montrent que le nouveau système de façade proposé offre une amélioration significative de la stabilité mécanique et de la durabilité à long terme.

En particulier, deux aspects innovants ont été étudiés et réalisés. D'une part, il a été constaté que l'application d'un apprêt profond sur le substrat favorise un meilleur durcissement du liant minéral, améliorant ainsi les propriétés mécaniques globales. En fait, il a été démontré que les substrats peuvent avoir un impact important sur la stabilité de l'enduit en raison de la séquestration de l'eau une fois l'enduit appliqué. Cet effet peut être contrôlé, comme le montre ce projet, par l'application d'agents hydrophobes silane/siloxane sur le substrat. Le traitement de surface augmente le degré d'hydratation de la matrice minérale, améliorant ainsi les propriétés mécaniques dans une certaine mesure.

En outre, il a été prouvé que la solution peut être appliquée efficacement à une large gamme de substrats, tels que le béton, les briques d'argile, les blocs de silicate de calcium et les pierres naturelles, en obtenant dans tous les cas une hydrophobisation partielle de la surface. D'autre part, au niveau du système, ce projet fournit une configuration de l'ETICS, en plus du traitement de la surface, l'inclusion de fixations mécaniques au mortier adhésif protecteur/maillage incorporé, améliorant encore la robustesse et la durabilité à long terme du système constructif.

Du point de vue de la faisabilité commerciale et économique, ce projet permet de mieux comprendre les coûts de rénovation des solutions traditionnelles et des solutions en aérogel, sur la base de l'analyse de chaque aspect de la rénovation, présentant ainsi un calcul des coûts plus réaliste. En particulier, il a été constaté qu'en utilisant une isolation en aérogel à haute performance (λ>20mW/m-K), et encore plus d'enduits aérogel, les coûts de main d'œuvre peuvent être réduits (ce qui est particulièrement coûteux en Suisse). En effet, les résultats de l'analyse montrent qu'en considérant tous les coûts d'une rénovation, y compris les aspects qui ne sont généralement pas pris en compte dans les budgets de rénovation, tels que la reprise des détails de la façade, les embrasures de fenêtres et les raccordements

et terminaisons, les coûts de l'utilisation d'une isolation traditionnelle sont souvent beaucoup plus élevés que prévu.

Néanmoins, les performances plus élevées des produits en aérogel et même des aérogels plus performants favorisent une réduction importante de ces coûts, ce qui permet d'obtenir des coûts de rénovation globaux finaux beaucoup plus compétitifs. En fait, il est possible d'atteindre des normes d'isolation plus élevées sans rénovation profonde des façades à l'aide d'aérogel, ce qui permet d'obtenir des subventions de l'administration fédérale. En effet, grâce à ce projet, un outil en ligne gratuit permettant d'obtenir une estimation des coûts et des économies potentielles a été développé. Il fournit des calculs réalistes pour une rénovation utilisant une isolation traditionnelle et une isolation à l'aérogel, montrant que l'isolation à l'aérogel est plus compétitive que prévu. L'outil a le potentiel d'améliorer la dynamique du marché de l'isolation aérogel pour une meilleure pénétration du marché de ce type de produits et devrait être activement utilisé pour promouvoir l'isolation aérogel. Néanmoins, le potentiel le plus important peut être atteint par les enduits aérogels ultra performants en termes de coût global, ce qui est donc plus faisable sur le plan économique.

Enfin, la mise en œuvre des résultats de ce projet se fera par le lancement sur le marché d'un enduit aérogel haute performance par Aeroskin Tech AG à court terme, et la distribution sur le marché de ce dernier enduit aérogel par Agitec AG. En outre, la plateforme en ligne gratuite sera largement utilisée par Agitec AG pour la commercialisation de l'enduit aérogel d'Aeroskin Tech, mais aussi pour sa large gamme de produits aérogel et de systèmes de façade.

Les résultats ont déjà été mis en œuvre par l'introduction d'apprêts profonds dans les systèmes de façade et leur effet sur la capacité d'absorption d'eau des matériaux de construction, en particulier ceux utilisés dans les façades des bâtiments. Les connaissances ont déjà été partiellement mises en œuvre au semestre d'automne dernier dans le cours de matériaux 3 "Physique du bâtiment" pour les ingénieurs civils, de l'Institut des matériaux de construction à D-BAUG - ETH Zurich. Néanmoins, d'autres concepts seront appliqués, en particulier en ce qui concerne les systèmes d'isolation à base d'aérogel, entre la fin de cette année et l'année prochaine.

D'un point de vue technologique, les prochaines étapes devraient être axées sur l'amélioration du rapport global entre les propriétés mécaniques et l'isolation thermique afin de réduire davantage la conductivité thermique dans les enduits aérogels. En fait, il a été démontré que plus la capacité d'isolation thermique d'un enduit aérogel est faible, plus la réduction des coûts totaux est importante. D'un point de vue commercial, l'utilisation et la validation à grande échelle de l'outil en ligne fourni devraient améliorer l'adoption par le marché des produits aérogels et en particulier des enduits aérogels à haute performance qui ont un potentiel commercial plus élevé.

Summary

Aerogel insulation renders, in contrast to aerogel boards/blankets, have not yet achieved their full potential in terms of thermal insulation performance. In this sense, the thermal conductivity of aerogel renders (λ>28mW/m·K) is more than twice compared to the aerogel granules used (λ=13 mW/m·K). Nevertheless, aerogel renders could provide a much better cost/benefit compared to aerogel boards, as the cost of the granules are 60% cheaper compared to the latter. Additionally, the installation costs are also estimated to be lower, proving the potential to reduce the overall renovations costs by >25%, being also competitive vs. mass market. However, the barriers to achieve high-performance renders exist at different levels, particularly related to the application, robustness and structural stability of the constructive system. Moreover, the marketing strategy of thermal insulation in general is not beneficial to aerogel products, as it doesn't show economically the competitive advantage of aerogel solutions in comparison to traditional materials. In particular, costs savings in man labour are not well understood, requiring a deep analysis on the final renovation costs using different type of products.

This project provides solutions to tackle the above-mentioned barriers. In particular, from the technical point of view, this project brings technological innovation to enhance, during the application, the robustness of aerogel insulation renders with low mechanical properties based on mineral binders. In this sense, the project demonstrates the innovation through the application of an enhanced ETICS system based on a new high-performance aerogel render through the renovation of 40m^2 façade of a villa in Lenzerheide.

Additionally, a modular construction with testing plates with the same façade setup has been built to perform the study. In this sense, the methodology consisted in durability and physical tests during one year for two types of mineral aerogel renders, allowing the comparison of different aspects of the material properties. The results show that the new proposed façade system provides significant improvement in mechanical stability and long-term durability.

In particular, two main innovative aspects have been studied and achieved. On the one hand, it has been found that the application of a deep primer on the substrate promotes a better curing of the mineral binder through, thus improving overall mechanical properties. In fact, it has been shown that substrates can have a high impact on the stability of the render due to water sequestration once the render is applied. This effect can be controlled, as shown in this project, by the application of silane/siloxane hydrophobizing agents to the substrate. The surface treatment enhances the degree of hydration of the mineral matrix, thus improving the mechanical properties up to some extent.

Moreover, it has been proven that the solution can be effectively applied to a wide range of substrates, from concrete, clay brick, calcium silicate block and nature stones, achieving in all cases, a partial hydrophobization of the surface. On the other hand, at a system level, this project provides a configuration of the ETICS, in addition to the surface treatment of the surface, the inclusion of mechanical fixations to the protective adhesive mortar/embedded mesh, enhancing further the robustness and long-term durability of the constructive system.

From the commercial and economical feasibility point of view, this project provides a better understanding of the renovation costs of traditional and aerogel solutions, based on the analysis of every aspect of the renovation, thus presenting a more realistic cost calculation. In particular, it has been found that using high-performance aerogel insulation (λ>20mW/m·K), and even more aerogel renders, the man-labour costs can be reduced (particularly expensive in Switzerland). Indeed, the results of the analysis show that considering all the costs of a renovation, including aspects typically not taken into account in renovation budgets, such as façade details rework, window reveals and connections and terminations, the costs of using traditional insulation is often much higher than expected.

Nevertheless, the higher performance of aerogel products and even more high-performance aerogel renders promotes and important reduction on such costs, ending up in much more competitive final overall renovation costs. In fact, the achievement of higher insulation standards can be obtained without

deep façade renovations using aerogel, providing the benefit of obtaining subsidies from the federal administration. Indeed, through this project, a free online tool to get a cost estimation and potential savings has been developed, which provides realistic calculations for renovation using traditional and aerogel insulation, showing that aerogel insulation is more competitive than expected. The tool has the potential to improve the market dynamics of aerogel insulation for a better market penetration of such type of products and is expected to be actively used to promote aerogel insulation. Nevertheless, the biggest potential can be achieved by ultra high-performance aerogel renders in terms of overall cost, thus more feasible economically.

Finally, the implementation of the findings of this project will be achieved in through the market launch of a high-performance aerogel render by Aeroskin Tech AG in the short term, and the market distribution of the latter aerogel render by Agitec AG. Moreover, the free online platform will be widely used by Agitec AG for the commercialisation or Aeroskin Tech aerogel render, but also for their broad range of aerogel products and façade systems.

Further implementation of the results has already taken place, by the introduction of deep primers in façade systems and its effect on the water absorption capacity of building materials, in particular, the ones used in façades of buildings. The knowledge has already partially been implemented last Fall semester in the Materials 3 course “Building Physics” for Civil Engineers, of the Institute for Building Materials at D-BAUG – ETH Zurich. Nevertheless, more concepts will be applied, in particular related to aerogel insulation systems between later this year and next year.

Next steps from a technological point of view should be focused in improving overall ratio between mechanical properties and thermal insulation in order to reduce the thermal conductivity further in aerogel renders. In fact, it has shown that the lower the thermal insulation capacity that an aerogel render can achieve, the better the reduction of total costs can be obtained. From commercial point of view, the wide-spread use and validation of the provided online tool should improve the market adoption of aerogel products and in particular high-performance aerogel renders with higher market potential.

Main findings

The project has shown how aerogel insulation renders based on mineral binders with low mechanical properties can enhance their robustness during the application. In this sense, the innovation and study of this project provides how to perform an advanced ETICs system using aerogel renders to obtain higher mechanical properties and durability by:

- Promoting a better curing of the mineral binder through the application of a deep primer on the substrate, and with this, enhanced mechanical properties of the aerogel render. Key aspects related to achieve this benefit are:
    - Substrates can have a high impact on the stability of the render due to water sequestration once the render is applied.
    - This effect can be controlled by the application of silane/siloxane hydrophobizing agents to the substrate.
    - The surface treatment can enhance the degree of hydration.
    - The effect of the hydrophobzing agent is effective in a wide range of substrates, from concrete, clay brick, calcium silicate block and nature stones.
- The inclusion of mechanical fixations to the protective adhesive mortar/embedded mesh can be used to enhance the robustness and long-term durability of the constructive system (ETICS).

Moreover, the project has achieved a better understanding of the renovation costs based on the analysis of every aspect of the renovation.

- High-performance aerogel insulation (λ>20mW/m·K), and in particular aerogel renders, reduces the man-labour costs (particularly expensive in Switzerland).
- Considering all the costs of a renovation, including aspects typically not taken into account in renovation budgets, such as façade details rework, window reveals and connections and terminations, the costs of using traditional insulation is often much higher than initially expected.
- The higher performance of aerogel products and even more high-performance aerogel renders promotes and important reduction on costs typically not considered initially, ending up in a much more competitive overall renovation costs.
- Higher insulation standards can be achieved without deep façade renovations using aerogel.
- Aerogel insulation can be more suitable to obtain subsidies from the federal administration for enhanced thermal insulation renovations.
- A free online tool to get a realistic cost estimation and potential savings has been developed.
- Aerogel insulation is more competitive and more feasible economically than expected.
- The biggest potential can be achieved by ultra high-performance aerogel renders in terms of overall cost and economic feasibility.

Contents

Abbreviations

D-BAUG - Dept. of Civil, Environmental and Geomatic Engineering

DoH – Degree of Hydration

EU – European Union

ETICS – External Thermal Insulation Composite System

Ldh: Dehydration

MDS – Material Datasheet

MSDS – Material Safety Datasheet

TG – Tiefengrund or deep primer

TGA – Thermogravimetric Analysis

XPS – Extruded Polystyrene

WP – Work Package

μ = Water vapour diffusion coefficient

1 Introduction

1.1 Background information and current situation

Motivations: ***Context: Climate related issues*** are affecting the population globally, whereas the construction sector has the highest implication in this matter. In this sense, buildings consume ***40% of the global energy and emit 36% of global man-made energy-related CO_2***. Europe and particularly Switzerland are not the exception, and an essential aspect of this problem is the ***lack of thermal insulation***. Because of the latter, the ***Swiss Energy Strategy 2050*** is promoting higher standards, by increasing the insulation layer substantially for both new buildings and retrofitting. In fact, the Building Program's criteria for receiving subsidies is: ***U-value of ≤0.20 (retrofitting) and ≤0.15 (new buildings)***. Using traditional mass market materials would require a ***layer thickness of up to 35 cm***, thus not suitable for ***main Swiss cities*** (with highest energy consumption and air pollution), where the ***space is highly limited and particularly expensive*** (~10k CHF/m^2). Such materials consequently reduce living area importantly, therefore ***impacting negatively the marketable property space of new buildings, or requiring deeper (and more expensive) renovation procedures for retrofitting***. Actually, the latter results in a low renovation rate of old buildings, as they can continue to be operative without been forced to perform a retrofit. Additionally, for those which are being superficially renovated, the ***regulation for renovation*** in Switzerland allows them to comply only with certain aspects related to reduce the energy consumption of the building[1]. In general, it should achieve an energy consumption of ***75 kWh/m^2/y*** or ~***7.5 L*** of heating oil/m^2 of heated living space. In principle, renovated façade walls should provide a ***U-value*** ≤ ***0.25 W/m^{2}K***, applicable only to the elements or areas of the building that would be renovated. However, ***a system verification can be proposed,*** instead of complying individual requirements. This often results in an unclear demarcation of the retrofit because only individual parts of the refurbishment require approval. Therefore, the retrofitted insulation thickness is typically limited to ***6-8 cm*** due to architectural limitations (thicker layers increase the costs substantially) unless a full renovation of the building is planned. Indeed, the thermal insulating performance of buildings older than 20 years, doesn't reach the retrofit regulation standards, even after a renovation, as shown in the next figure (Figure 2):

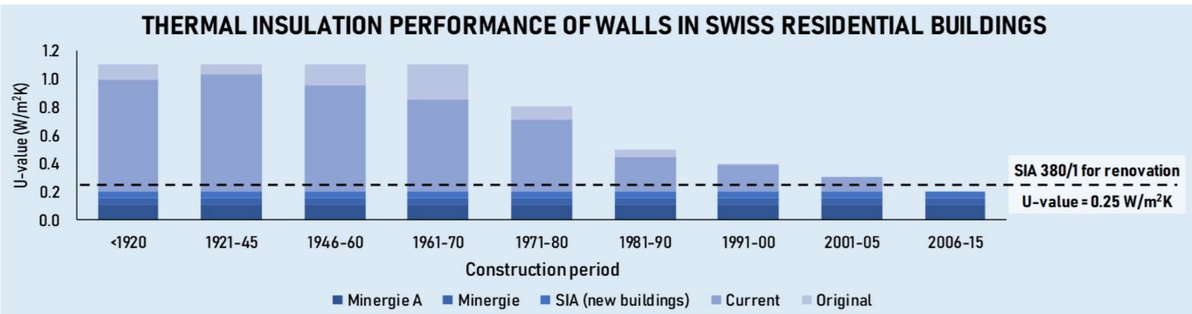

Figure 1. Thermal insulation performance of walls of current buildings in Switzerland according to their construction period. Lower values = better thermal insulation performance. Data from 2018[2].

The previous scenario shows that only having ***very cheap mass market insulation materials is not enough to promote energy retrofitting***. In fact, the cost of the insulating material itself is ***only 5% to 15%*** of the required investment. Indeed, most of expenses are related to installation and particularly the repairing needed in order to install the required thickness for a U-value ≤ 0.25 W/m^{2}K. Moreover, thick and traditional thermal insulation also increases fire risk ***when flammable insulation is used***. In fact, ***40% of the global market share*** of traditional thermal insulation, as well as many of the high-performance products available, are ***non-fire-resistant***, with ***high risk to the population*** (as seen on the tragedy of London's Grenfell tower in 2017, with 71 deaths).

[1] EnDK. (2018). *Vollzugshilfe EN-102: Wärmeschutz von Gebäuden. Basis: Norm SIA 380/1.* Konferenz Kantonaler Energiedirektoren: Bern.

[2] Streicher, K.N., *et al.* (2018). *Assessment of the current thermal performance level of the Swiss residential building stock: Statistical analysis of energy performance certificates. Energy and Buildings 178*, 360-378.

Possible solution: High-performance insulation (λ >20 mW/m·K) is a plausible solution to reach U-values ≤ 0.25 W/m²K, in the current limited space provided by superficial façade renovations, therefore, avoiding more expensive/deeper retrofits. In fact, the thermal insulating capacity of such products (boards and blankets) is typically twice or more compared to mass-market products, achieving the ***same performance in half the thickness or less***. Indeed, most of high-performance insulating materials are based in silica aerogel, the best thermal insulator known up to date. Silica aerogel is a highly (nano) porous material (pores >90% and mean pore size of 20nm: <1/3 of the mean free path of air), in which its internal structure prevents air molecules from colliding with each other, thus virtually eliminating convection within the material. However, the cost/benefit of the existing limited market's offer on high-performance insulation is not attractive, increasing the overall cost way beyond a traditional solution, especially due to the fact that ***aerogel blankets and boards are expensive, with a sales price ~50 CHF/kg (150 kg/m³)***. However, ***silica aerogel in form of granules is less expensive, with a market price of ~20 CHF/kg as raw material***, therefore, they ***could provide a better cost/benefit relation today, and even more in the future due to its forecasted economy of scale***. In fact, a widespread adoption of silica aerogel is anticipated for building insulation, expecting to generate ***a price drop of up to 70%, once much higher aerogel volumes are commercialized, probably to be triggered by aerogel granules***. Nevertheless, in contrast to blankets and boards, aerogel granules are not finished, ready to apply products (unless purred into wall or glass cavities), consequently, they need to be integrated into a composite material. Even though, despite that silica aerogel particles are commercially available since almost a couple decades and enormous efforts for developing aerogel composites with mineral binders have been made (national and multinational projects within Europe and world-wide), none of the aerogel renders commercially available offer high performance thermal insulation. In fact, they offer the ***same or worse thermal insulation capacity than traditional insulation***, thus not compensating their higher costs either. Therefore, there is no high-performance product in the market that can be sprayed, an application technique ideal for retrofitting in order to properly adapt to non-flat surfaces of old buildings, but also ***with lower installation costs compared to insulating boards***, also attractive for new buildings.

In summary, granular aerogel-based insulation renders, in contrast to aerogel boards/blankets, have the ***potential to provide higher performance at lower cost***, however such solutions have not yet achieved their full capacity in terms of thermal insulation performance. In fact, the thermal conductivity of aerogel renders (λ>28mW/m·K) is twice and more compared to the aerogel granules that they contain (λ=13mW/m·K).

Barriers for high-performance aerogel renders: The barriers to achieve better insulating performance in aerogel renders exist at different levels, however, those are always ***bound to the mechanical properties***, thus robustness of the solution. On the one hand, at a ***material level***, the increase in thermal insulation performance is achieved by increasing the proportion of aerogel in respect to the mineral binder, increasing the overall aerogel loading. Nevertheless, current scientific research has shown that there is a compromise with this proportion and the resulting mechanical behaviour, whereas optimization of the composite's microstructure can improve this relation[3]. Nevertheless, current aerogel renders are sometimes below the mechanical requirements in practice, resulting in brittle materials. On the other hand, the limited mechanical properties of aerogel renders become therefore ***more critical at a system level***, with a much higher compromise towards the overall constructive system's stability (particularly in the mid to long term) where ***the aerogel render interacts with the substrate and protective layers***. In fact, debonding of layers in aerogel render systems can happen in practice, potentially generating deep structural damages. Indeed, debonding of layers occurred in an earlier ***renovation in Switzerland in 2020*** (project undisclosed)***, using an aerogel render (Figure 3)***. In this sense, the application was apparently satisfactory at first place, nevertheless, months later, internal cracking and detachment of layers occurred, requiring to remove the whole external insulation and replacing it with another solution (work to be performed in the upcoming weeks).

[3] Sanz-Pont, Daniel, et al. (2016). *Anhydrite/aerogel composites for thermal insulation. Materials and Structures 49.9, 3647-3661.*

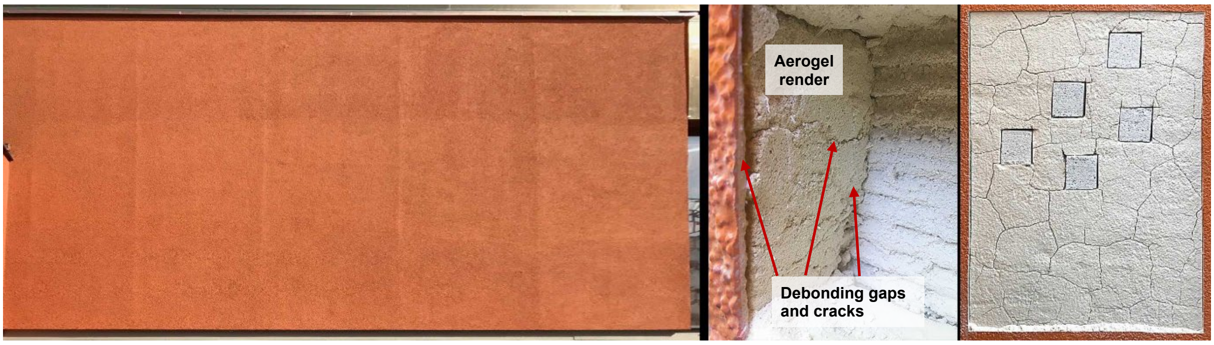

Figure 2. Earlier case study in Switzerland. Left: View of a façade of the building after the renovation with an aerogel render system. Centre: Detail from the inspection showing cracking and debonding of the aerogel render. Right: Larger inspected area showing the aerogel render fully cracked.

Indeed, silica aerogel renders have many challenges not visible at the lab scale, which are ***related to its application as an insulation system***. In this sense, scientific research showed that the mineral binder requires proper hydration to develop better mechanical properties[3]. However, the interaction of the aerogel render with the substrate and the environment does not provide proper curing (on-site), thus affecting hydration mechanisms of the mineral matrix. In fact, the substrate tends to sequestrate the water from the aerogel render in an early stage. This phenomenon occurs at different levels depending on the nature of the substrate (concrete, stone, brick and so forth), which can lead to ***cracking and chemical shrinkage of the render, leading to debonding*** from the two layers in contact with the aerogel render, as observed in the earlier case study mentioned before.

Moreover, a deep cost analysis of the whole renovation has not been performed, whereas just a few projects mentioned only the sales price of aerogel compared to traditional insulation, ***without installation and repair costs***, leading to an incomplete and unrealistic direct comparison. This always results in an unfair quantification, as in traditional insulation, the ***driving factors for the whole cost are installation and repairing (renovation)***, usually representing between 85% and 95% of the total cost, whereas the cost of the insulation material itself is not representative. Therefore, this ***P+D project is aimed to fill this gap***, ***providing new insights on developing aerogel render systems,*** in order to deal with the challenges and requirements in the application. Moreover, it will also provide an overall cost analysis for using aerogel renders in energy retrofit in different scenarios (levels of repair), compared to traditional insulation and aerogel blankets/boards, considering different levels of insulation (U-values) and level of detail of the façade to renovate, therefore, comparing the solutions on a broad level.

1.2 Purpose of the project

Project goals: The P+D project is aimed to perform development and testing on two main aspects of aerogel renders at a system level. First, focused on improving the ***technical feasibility*** of aerogel renders as an overall constructive system, especially to ease the implementation of high-performance solutions. Second, focused on assessing the overall cost required for the investment in such systems for retrofit, throughout field testing during the application of an aerogel render on a demonstrator building, but also through surveys and interviews from construction and renovation companies, considering different factors, scenarios and type of insulation, therefore, analysing the ***economic aspects*** of the technology.

Technical feasibility goal: Improve the mechanical robustness of aerogel renders at a system level in the short and long term, towards easing the implementation of high thermal performance mineral aerogel composites.

Economical feasibility goal: Provide an online platform that can generate an overall cost analysis for using aerogel renders in energy retrofit in different scenarios (levels of repair and insulation thickness), compared to traditional insulation and aerogel blankets/boards, including the targeted level of insulation (U-value) and level of detail of the façade to renovate).

1.3 Objectives

Technical feasibility: The short and long-term mechanical behaviour of aerogel renders in their implementation are affected by the highly variable conditions of the application at a system level, showing issues not visible at lab scale and with a controlled environment, therefore, compromising the overall structural stability of the constructive system. In this sense, the mineral binders that compose the matrix of the aerogel composite are at an extremely low volume proportion compared to the aerogel granules, in order to reach an overall low thermal conductivity, and even more for reaching a much higher thermal performance. Due to the latter, the composite requires a good consolidation and the mineral matrix needs to develop a high degree of hydration[3], otherwise the mechanical properties, and particularly the bonding performance can be compromised. However, during the on-site application on the substrate of a building, the water of the matrix tends to be sequestrated at different levels depending on the material to which the render is applied to. Particularly, the more porous and capillary active the substrate is, the higher the water uptake from the aerogel render will happen. This means that for materials with very high capillary suction, such as clay bricks or porous stones, the sequestration can happen within minutes or hours from the application, avoiding a proper material consolidation and restricting the degree of hydration (DoH) of the mineral binder. In some cases, the negative effect can be apparently negligible during the application, however, presenting a structural collapse of the system on the longer term, due to a decrease of the mechanical properties generated by the late-stage chemical and drying shrinkage phenomena.

Economical feasibility: Aerogel based thermal insulation, particularly blankets/boards are well known to be high end/high price solutions, nevertheless, sprayed aerogel insulation renders, based on aerogel granules, have the ***potential to provide a more cost-effective solution***, particularly if the render can provide ***high-performance thermal insulation***. In general, the overall required investment for energy retrofit of buildings includes several costs beyond the thermal insulation itself, such as scaffolding, cleaning, installation costs and repairing.

One the one hand, while most of these costs when using insulating boards are known and depend on the skills and quality of the workers, among other factors, the costs for repairing also depend on the state of the building. However, a common factor is given by the thickness of the insulation that would be installed, resulting in reworking and repairing of the architectural details and windows frames of the façade, particularly when the insulation cannot be installed in the limited space available. On the other hand, in contrast to insulating boards, the yield or productivity per square meter of the installation of aerogel renders depends on the thickness, as the procedure is an additive spraying process until reaching the desired target. This factor presents, in addition to the lower material costs vs. aerogel boards and blankets, an added ***competitive advantage for aerogel renders in terms of the overall cost***, as the mechanical application of the latter are much faster compared to the manual process of installing insulating boards.

Nevertheless, the is no information publicly available that provides a deep analysis on all the factors related to the overall costs of a renovation, particularly for aerogel renders (independently on their performance) and compared to aerogel blankets or traditional insulation.

From the novelty point of view, this project is also aimed to ***solve the open question regarding installation and repair costs, especially when using aerogel renders***. In this sense, in contrast with insulating boards (applied manually), the installation costs of aerogel renders (applied by spraying pumps) depend on the required thickness, whereas the application by machine is much faster, but with a much higher cost variation. An estimation based on ***other types of insulation renders*** has been done as ***preliminary information*** (from sources of other EU countries[4]) that ***needs to be validated***, in order to have a more precise cost estimation on aerogel render systems (Fig. 3, left).

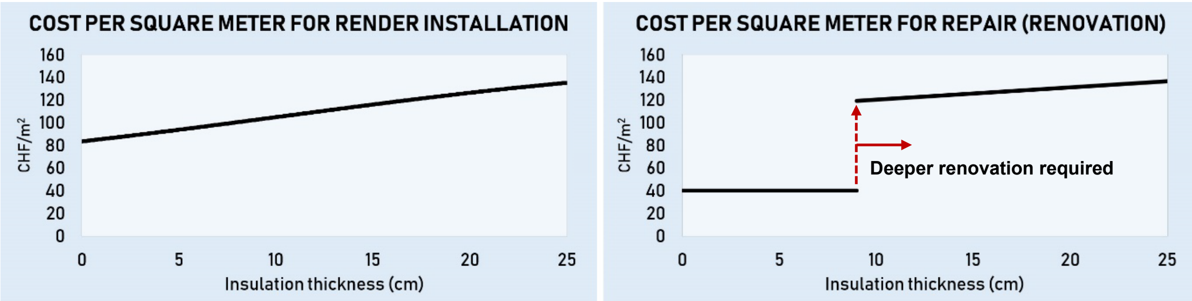

Figure 3. Left: Cost per square meter for render installation depending on the thickness for non-aerogel renders[4]. Right: Estimated cost per square meter for repair in renovation, depending on the insulation thickness based on[5,6].

A similar case to the installation costs occurs with the repairing required before the installation of the thermal insulation, as shown in the previous figure. In this sense, depending on the ***state of the building and the required thickness***, the repairing costs in renovation can also have ***a very high variability***. In particular for retrofitting, the existing façade finish needs to be removed before installing the insulation. This procedure usually costs around 40 CHF/m^2, and it provides more space to install de insulation system. However, if the insulation requires more than 8-9 cm, it is typically needed to perform a ***deeper renovation***, requiring working on detailing, window framing, and so forth, therefore ***increasing the repairing costs dramatically up to 150 CHF/m^2***. Nevertheless, these costs ***have been estimated using data from Swiss sources***[5,6] that does not give a high degree of detail in order to precisely isolate all possible variables. Therefore, a ***validation on repair costs in relation to thermal insulation thickness is also required***, especially to have a direct empirical comparison for the different thermal insulating systems from WP4 and currently performed renovation. In order to have a full cost analysis, the analysis will also include all the other related costs for the renovation such as scaffolding, cleaning and so forth.

[4] www.prix-construction.info
[5] www.renovero.ch/de/tipps/fassaden/fassade-renovieren-kosten
[6] www.ofri.ch/kosten/fassade-renovieren

2 Description, procedures and methodology

The P+D project will be structured for solving and demonstrating two main issues: First, ***increasing the overall constructive system robustness of aerogel renders (system level)*** and second, focused on ***investigating the overall façade renovation costs when using aerogel renders*** in comparison with other solutions. The system's demonstration and cost analysis will be performed from two different approaches: First, through the renovation of a concrete façade of a mountain villa, performing a detailed cost analysis, and second, through surveys from existing retrofitted buildings in Switzerland from different sizes and insulation levels. The project will be divided in 6 work packages, plus an extra WP regarding the project closure (WP7):

General project planning:

WP1 (Planning): Planning of the details of the demonstrator project (3 months), including the development of the project architectural plans, purchasing insulation and materials and hiring a subcontractor (renovation work).

Overall constructive system robustness:

WP2 (Testing and optimization of different substrates): To solve the technical limitations of aerogel renders during their application on different substrates and particularly towards achieving robust aerogel render systems, research on coatings to control and limit the water uptake from the substrate will be performed. This WP will be focused in finding the optimum coating for improving the mechanical properties and bonding of the system's layers and to promote a high degree of hydration of the mineral binder of the aerogel render.

- ***Methodology:*** The coating and water uptake tests will be performed on 5 different construction materials: clay brick, concrete, sand stone, lime stone and repair mortars. In particular, capillary rise and water absorption of the different substrates will be assessed on 40x40x160 mm prisms, testing different market products to control water uptake. The results will be evaluated, on the one hand, by measuring the amount of water in grams per unit time, using a scale with a precision of 0.01 g, in order to assess both rate of water absorption and total water absorption capacity. On the other hand, the height of capillary rise will be assessed by measuring the height in cm to which the water rises within each material. This test will be performed using and infrared camera (FLIR E8) and a digital calliper.

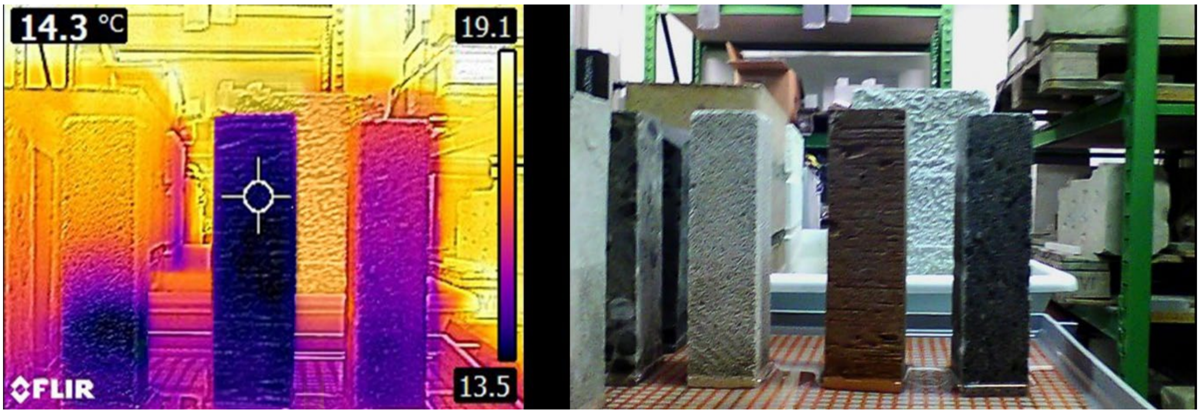

Figure 4. Example of capillary rise assessment through infrared camera. Pictures from Building Physics lab (Materials III for Civil Engineering at D-BAUG, ETH Zürich).

The solution will be selected upon achieving optimal results, therefore, considering the effectiveness of the product in relation to the number of layers to limit as much as possible the water uptake (capillary rise and water absorption). This WP will be developed in parallel to WP1.

WP3 (Modular wall for lab testing): The optimum solution obtained from WP2 will be tested to assess its effect on the mechanical properties (bonding and compressive strength), as well as the degree of hydration of two mineral aerogel renders, integrated within the construction system. The tests from this WP will be focused on measuring the impact of the coating in both short and long term, under outdoor on-site conditions, and in combination with the 1:1 scale application from WP4. These tests will be performed though a modular wall (Figure 7) that will be constructed at the location of a villa in the mountain (Lenzerheide, Canton Graubünden, WP4). The two different aerogel renders that will be tested at a system level are: ***Render 1***, an aerogel render with currently best performance in the market in terms of thermal conductivity (λ~28 mW/m·K) and ***Render 2,*** an underdevelopment higher performing aerogel render (λ~17 mW/m·K). This will allow to test the evolution of their material properties, therefore, its mechanical robustness. The wall will consist in smaller modules that will provide systematic testing of each solution every month (1 concrete slab and 1 clay brick slab for each render), for a total of 12 months.

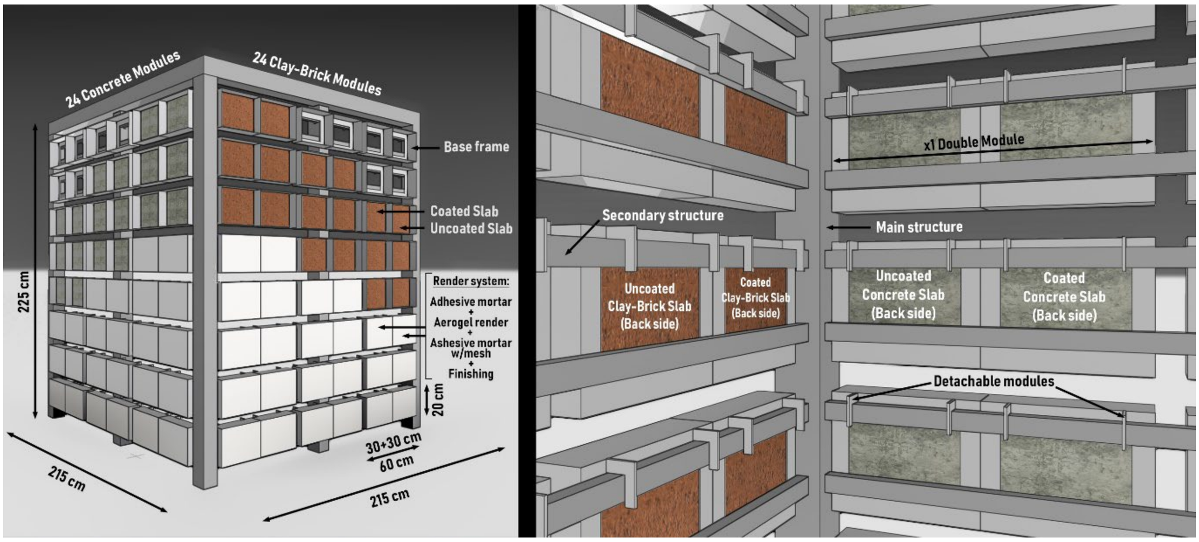

Figure 5. Initial sketch of complementary wall with slab modules for testing long term weathering in the mechanical properties (compressive strength and bonding) and degree of hydration for two aerogel renders.

- ***Methodology:*** Construction and testing of a complementary wall at the villa location composed by detachable modules. In particular, 24 concrete slab modules and 24 clay brick modules of 60x20x2cm (12+12 per render). Each module will consist in 2 submodules (30x20x2 cm) to which one of the submodules will be treated with the selected coating from WP2, and the other one without coating (as a reference). Additionally, the insulating renders and other layers will be applied to both submodules in order to replicate the constructive system. The application will be performed during the façade renovation of the villa from WP4. Each set of modules (one per render) will be detached from the wall and tested every month, in order to assess the evolution of the mechanical properties and degree of hydration during 12 months:

    - o <u>Bonding strength tests:</u> Each sample will be tested for bonding strength at both sides of the aerogel layer through the pull-out method, using a Universal Testing device with a load cell of 10 kN (Zwick).
    - o <u>Compressive strength tests:</u> Samples of 40x40x40 mm will be obtained by cutting the modules (5 samples per sub-module), to which compressive strength tests will be performed using a Universal Testing device with a load cell of 10 kN (Zwick).
    - o <u>Degree of Hydration (DoH):</u> The degree of hydration of the render of each sub-module will be measured by performing thermogravimetric analysis (TGA) of the mineral phases (matrix) of the aerogel renders. These tests will be performed using a Quanta 50 TGA (TA Instruments).

Moreover, for quality control, additional samples will be collected and stored under lab conditions, to perform laboratory tests (thermal conductivity, compressive strength and shrinkage) at different ages: 7D, 28D and 3M.

- o <u>Thermal conductivity:</u> The thermal conductivity will be measured from samples of 200x200x20 mm of the renders through the standard ASTM C518-15 (Standard Test Method for Steady-State Thermal Transmission Properties), using a Lasercomp Heat flow meter FOX 200 (TA Instruments).
- o <u>Shrinkage:</u> The shrinkage (mm/m) of the renders will be assessed from the thermal conductivity samples,

considering the average value of the two longest sides of the sample, by measuring the length at the centre of the specimen after curing and drying, using digital calliper (precision of 0.01 mm). The measurement will be compared to the initial dimensions (200mm x 200mm) in order to obtain the final value in standard units.

All the tests from this WP will be performed at ETH Zurich, levering from the hosting of Aeroskin Tech in the Institute for Building Materials as an ETH Spin-off (hosting until end of 2023).

WP4: Villa in the mountain: The demonstration site will consist in a mountain villa in Lenzerheide (façade to be renovated of ~40m^2), based in concrete construction with the extreme winter conditions and environment of Swiss mountain locations (Figure 9). The aerogel render that will be used to test the constructive system will be the high-performance λ~17 mW/m·K render applied in WP3 (Render 2). The application will target a U-value of 0.25, as for renovation (6.5 cm). It will also include the coating and other layers to replicate the constructive system from WP3. Additionally, towards increasing even further the long-term constructive system's robustness, thermal-broken fixations will be integrated. The application is planned to begin 3 months after the start of the project (August 2021).

Figure 6. Views of the villa to be renovated in Lenzerheide, Graubünden, Switzerland. Application on the ground floor.

WP5: **Demonstrator's monitoring:** To complement the application tests from WP3-WP4, the demonstrator site will include the monitoring of the temperature, vapor diffusion, humidity and drying rate (using embedded sensors), in order to correlate the on-site's hygro-thermal conditions from the renders with the evolution of the mechanical properties (including bonding) and degree of hydration during 15 months (3M: assessing the drying rate/12M: fully dry monitoring). This will also allow to asses if the remaining humidity could generate differential thermal expansion, thus having a direct effect on the material's behaviour and bonding during winter and summer (freeze-thaw).

Façade renovation costs of aerogel renders:

WP6: Cost analysis: This WP will be focused in a detailed quantification of all the costs of the demonstrator after the renovation (WP4), with a particular focus on installation & repair costs. Additionally, it will include a broad survey from construction and renovation companies, in order to have as detailed as possible, a costs structure of façade renovation on different scenarios (type and level of insulation and repair). The outcome will be to generate an ***online platform where the general public will be able to a generate a cost estimation*** for their particular case, considering different levels of complexity and insulation (including the selection of the material), different building sizes and different proximities (daily travel distance for the workers of the renovation).

3 Activities, results and discussion

WP1 (Planning): The first step of the planning was to perform a site visit and measure the façade in order to gather all the required information and to perform the architectural drawings for the permits as well as the program. Some documentation as follows:

Figure 7. On-site check of the façade and the available space for installing the thermal insulation.

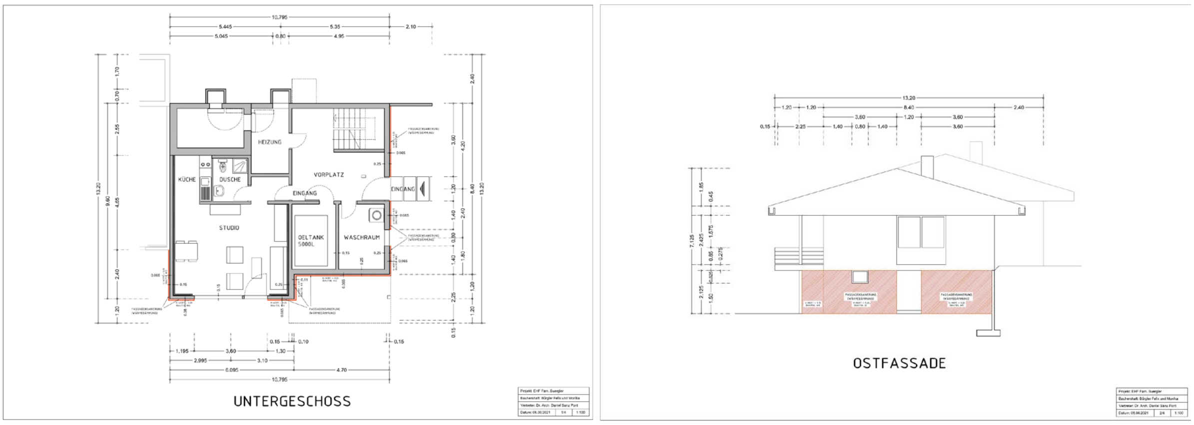

Figure 8. Floor plan and East façade drawings performed for the renovation of the villa.

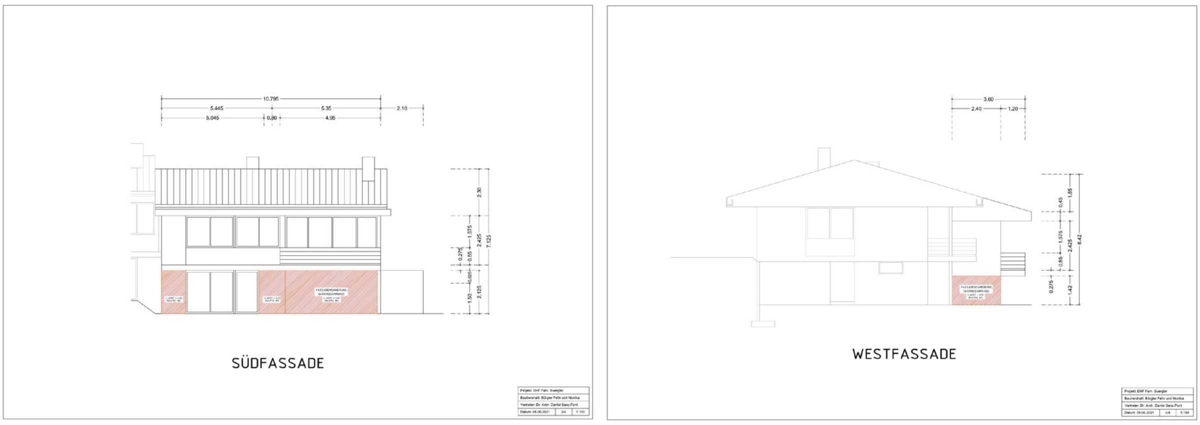

Figure 9. South and West façade drawings performed for the renovation of the villa.

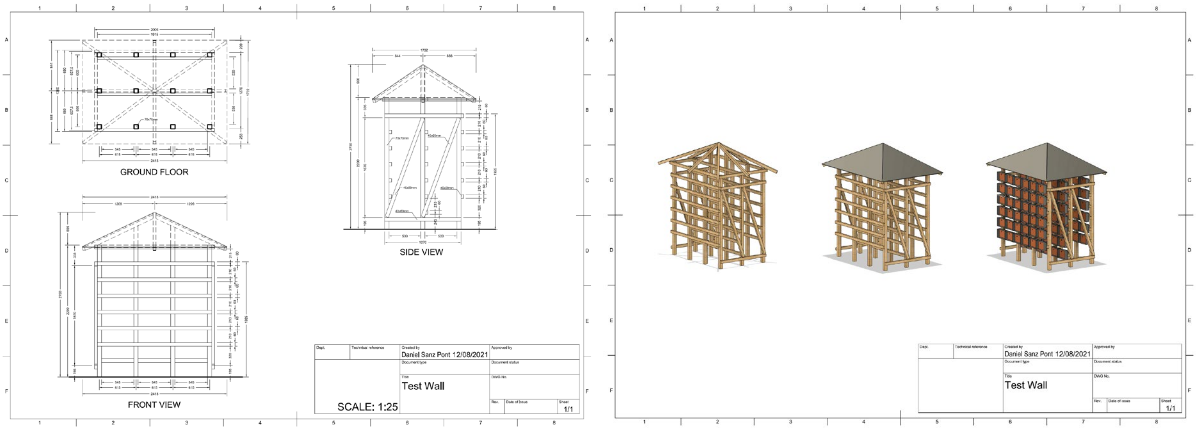

Figure 10. Constructive details of the wooden structure of the testing plates.

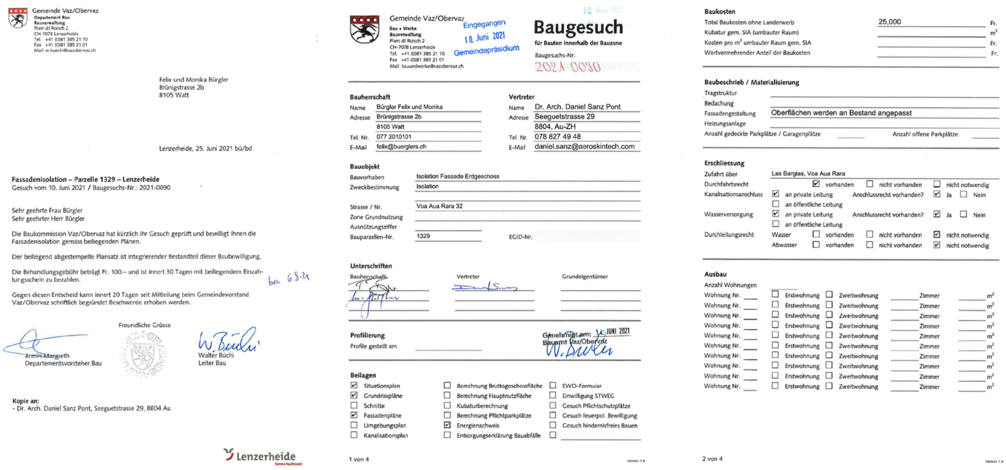

Figure 11. Some documentation of the construction permits of the renovation.

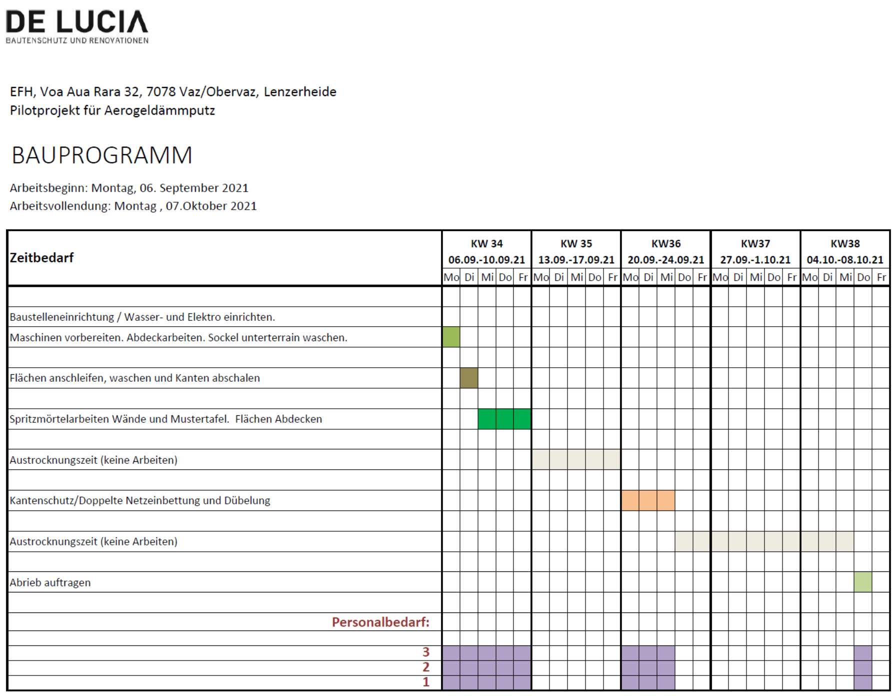

Figure 12. Schedule and activities of the renovation.

Figure 13. Some of the bags of the insulation renders to be applied in the façade and the testing plates.

WP2 (Testing and optimization of different substrates): Six different deep primers (Table 2) were selected and tested on different substrates (Table 1) to control the water absorption of the latter.

Table 1. Stones tested for capillary water absorption and coating treatment.

Stone	Bulk density (kg/m^3)	Porosity (%)
Clay Brick	1797	27.5%
Porous Concrete	2142	11.6%
Calcium Silicate Block	2000	14.0%
Concrete	2312	8.2%
Pre-Spray mortar	2094	20.9%
Sandstone (Bollinger Lehholz)	2441	4.0%
Limestone 1 (Mägenwiler gelb)	2245	6.6%
Limestone 2 (Mägenwiler blau)	2394	4.0%

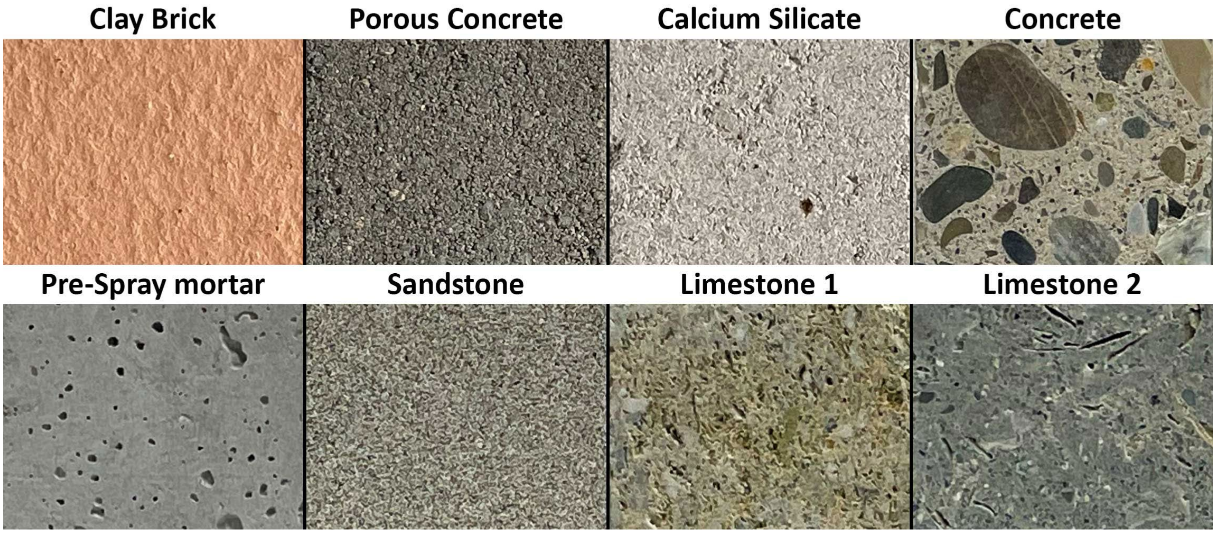

Figure 14. Stones tested for capillary water absorption and coating treatment.

Table 02. Products (deep primers) used for coating treatment and their chemistry (from MDS and MSDS).

Product	Chemistry
Product 1 (P01)	General: Synthetic resin dispersion, solvent-free Additional chemicals: Benzisothiazolinone, Methylisothiazolinone, Methylchloroisothiazolinone
Product 2 (P02)	General: Aqueous dispersion of copolymers in very finely divided acrylic acid esters Additional chemicals: Benzisothiazolinone, Methylisothiazolinone, Methylchloroisothiazolinone
Product 3 (P03)	General: Silicate with organic stabilizers, acrylate dispersion, additives, water Additional chemicals: N/A
Product 4 (P04)	General: Copolymer fine dispersion with mineral fillers Additional chemicals: Benzisothiazolinone, Methylisothiazolinone, Methylchloroisothiazolinone
Product 5 (P05)	General: Dispersion binder, Adhesion promoter, preservatives, fillers Additional chemicals: Benzisothiazolinone, Methylisothiazolinone
Product 6 (P06)	General: Emulsion silane / siloxane combination based, water repellent impregnation. Additional chemicals: Triethyl Trimethylpentyl Silane, Methylisothiazolinone

The deep primers applied in order to meet the following criteria: Capillary water absorption to be achieved by at least one product: >1.0 kg/m^2. Maximum applications: 3. The number of applications were as follows (Table 03):

Table 03. Number of applications of coating treatment per stone/product to meet criteria.

Stone	Ref	P01	P02	P03	P04	P05	P06
Clay Brick	-	3	3	3	3	3	1
Porous Concrete	-	3	3	3	3	3	1
Calcium Silicate Block	-	3	3	3	3	3	1
Concrete	-	1	1	1	1	1	1
Pre-Spray mortar	-	1	1	1	1	1	1
Sandstone (Bollinger Lehholz)	-	1	1	1	1	1	1
Limestone 1 (Mägenwiler gelb)	-	1	1	1	1	1	1
Limestone 2 (Mägenwiler blau)	-	1	1	1	1	1	1

The results of the water absorption of the substrates with the application of the deep primers were as follows:

Table 04. Capillary water absorption of stones and coating treatment (kg/m^2).

Stone	Ref	P01	P02	P03	P04	P05	P06
Clay Brick	25.3	23.6	22.7	24.7	24.1	1.5	0.7
Porous Concrete	4.1	1.2	1.2	5.2	0.9	1.2	0.6
Calcium Silicate Block	12.2	2.8	1.7	7.6	2.6	4.2	0.8
Concrete	2.3	0.8	0.9	1.9	0.7	1.3	0.3
Pre-Spray mortar	7.8	3.6	2.5	6.9	3.8	4.8	0.7
Sandstone (Bollinger Lehholz)	5.0	2.3	2.9	4.5	2.9	2.3	1.7
Limestone 1 (Mägenwiler gelb)	1.3	0.9	0.8	1.1	0.9	1.0	0.5
Limestone 2 (Mägenwiler blau)	1.4	0.8	1.0	0.9	1.0	0.9	0.9

The deep primer which gave the best results overall was the Product 06 (silane based):

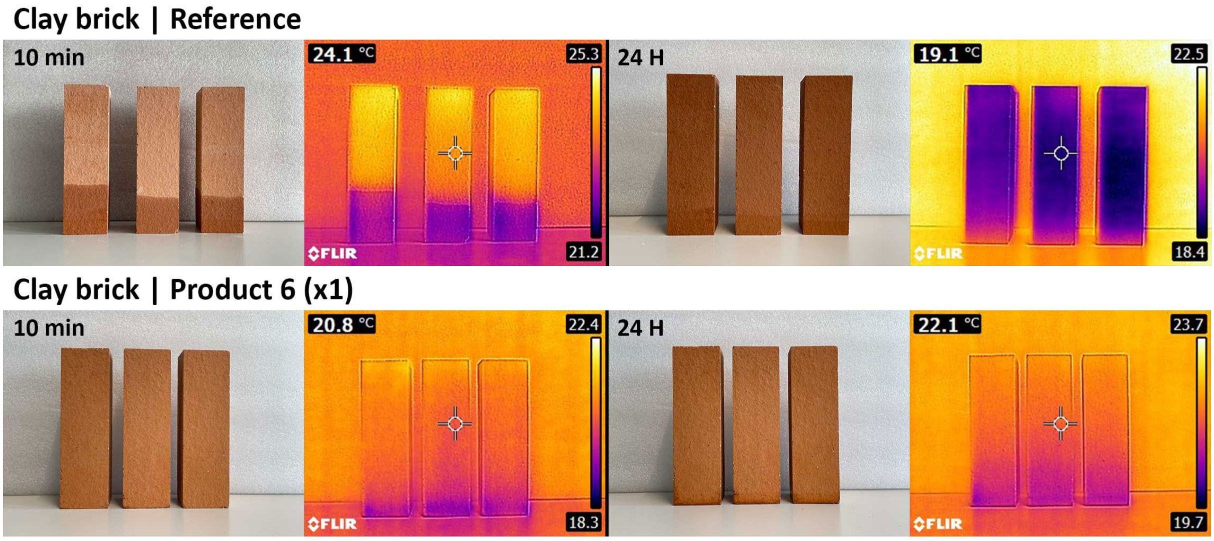

Figure 15. Tested clay brick prisms comparing the reference and the selected deep primer (product 06) for the coating.

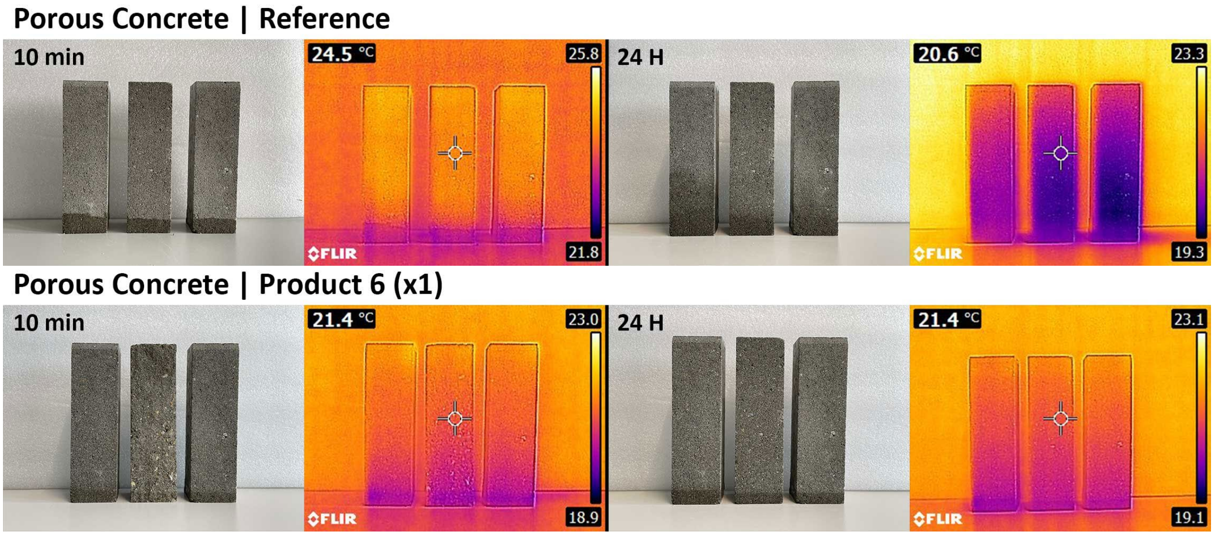

Figure 16. Tested porous concrete prisms comparing the reference and selected deep primer (product 06) for the coating.

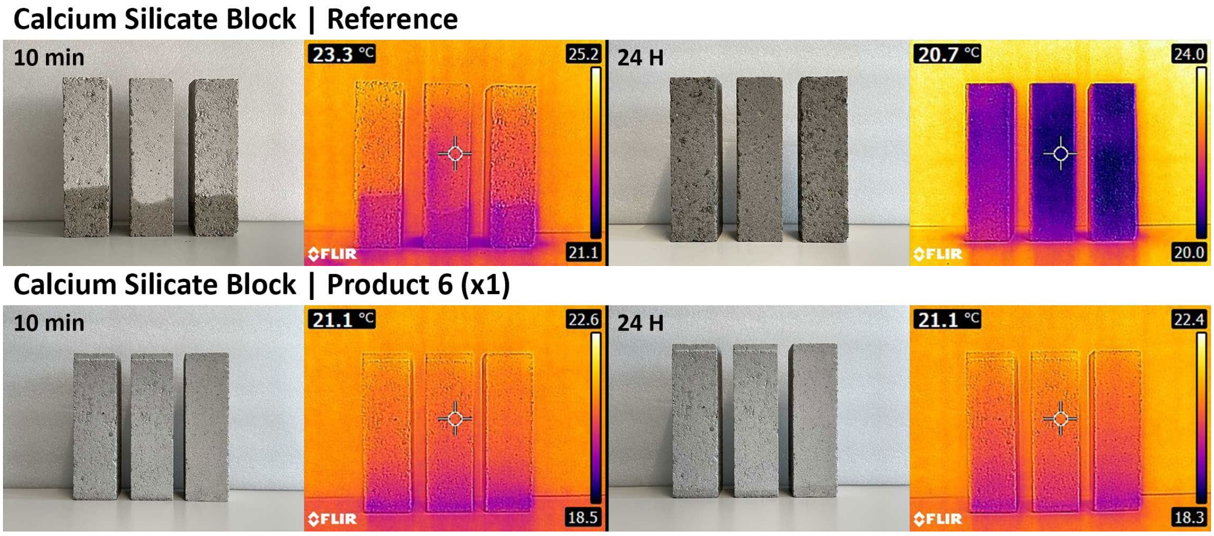

Figure 17. Tested calcium silicate prisms comparing the reference and selected deep primer (product 06) for the coating.

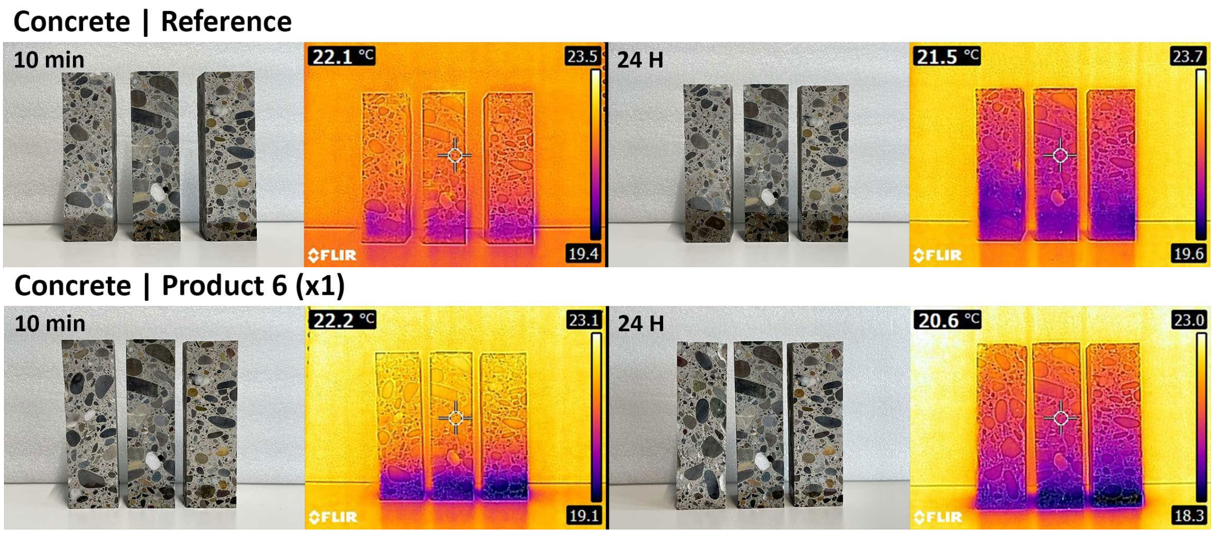

Figure 18. Tested concrete prisms comparing the reference and selected deep primer (product 06) for the coating.

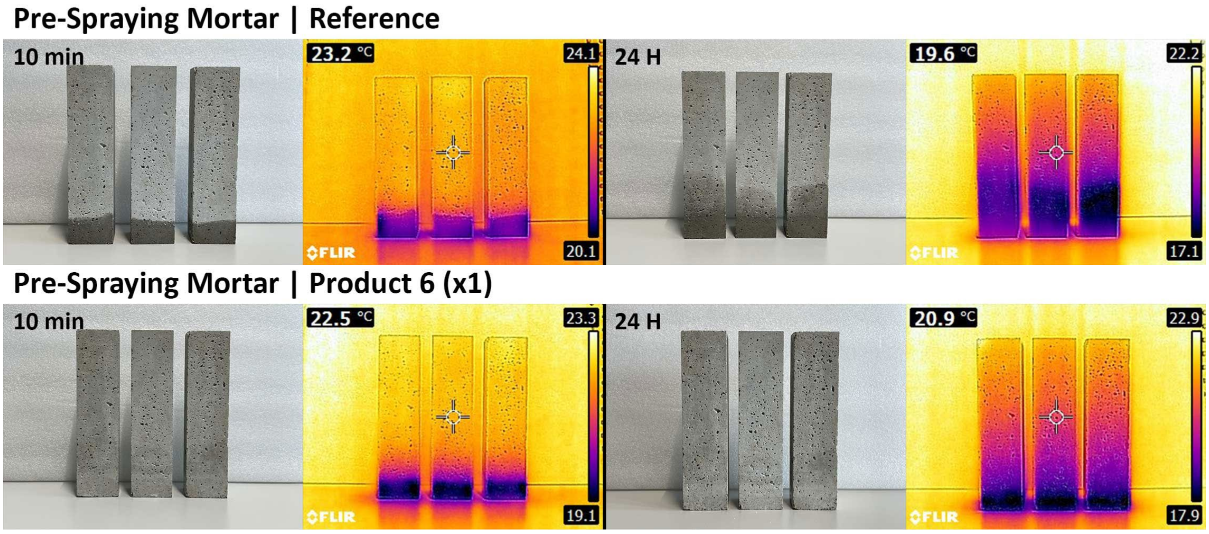

Figure 19. Pre-spraying mortar prisms comparing the reference and selected deep primer (product 06) for the coating.

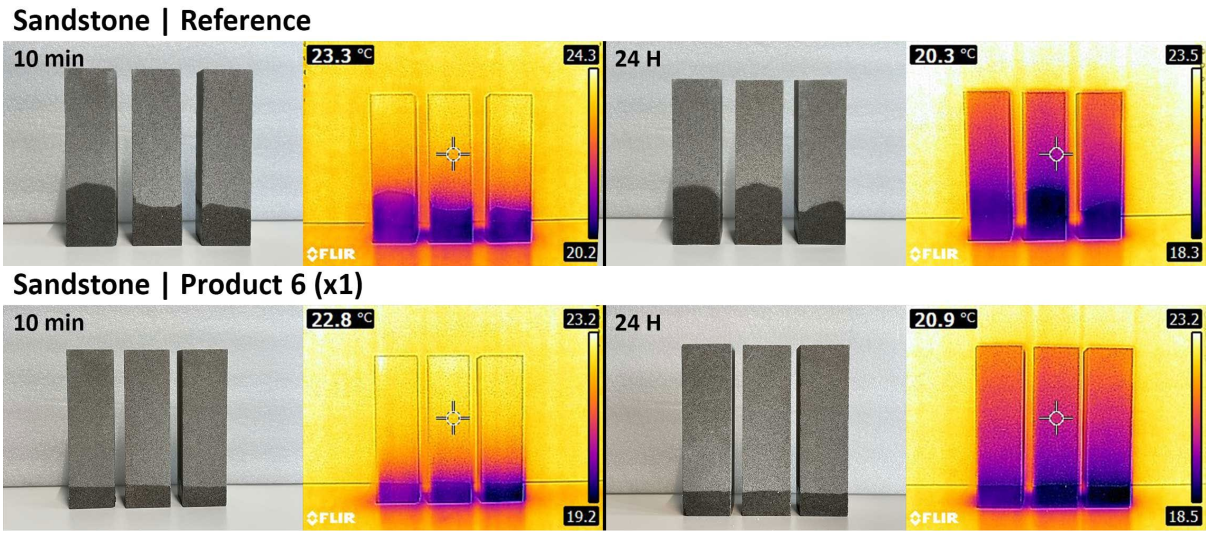

Figure 20. Tested sandstone prisms comparing the reference and selected deep primer (product 06) for the coating.

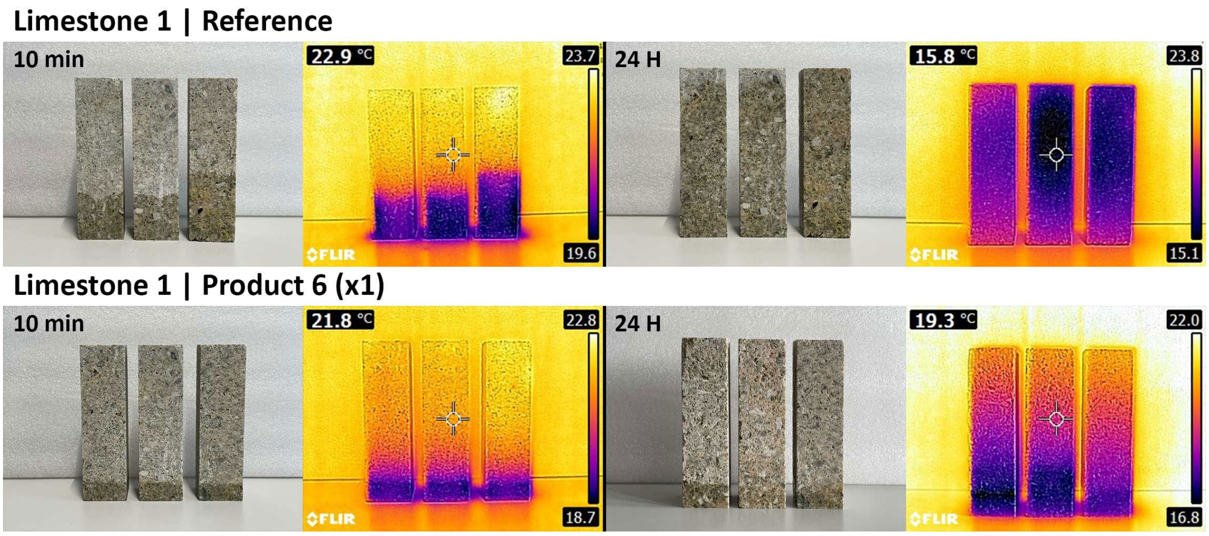

Figure 21. Tested limestone (1) prisms comparing the reference and selected deep primer (product 06) for the coating.

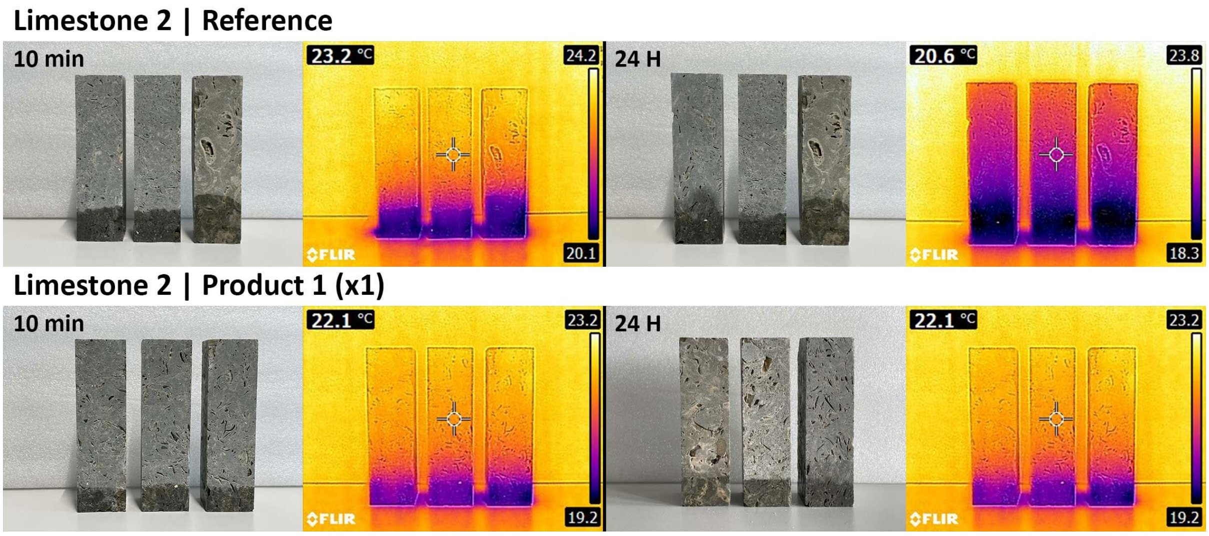

Figure 22. Tested limestone (2) prisms comparing the reference and selected deep primer (product 06) for the coating.

The following graphs show the evolution of the water absorption test in respect to saturation of the porosity of the stone in % as well as to the capillary water absorption in kg/m² for all the tested deep primers. This correlation is important as a high % of the saturated porosity does not necessary mean that the amount of water absorbed is high, thus, presenting a risk of too much water uptake from the aerogel render:

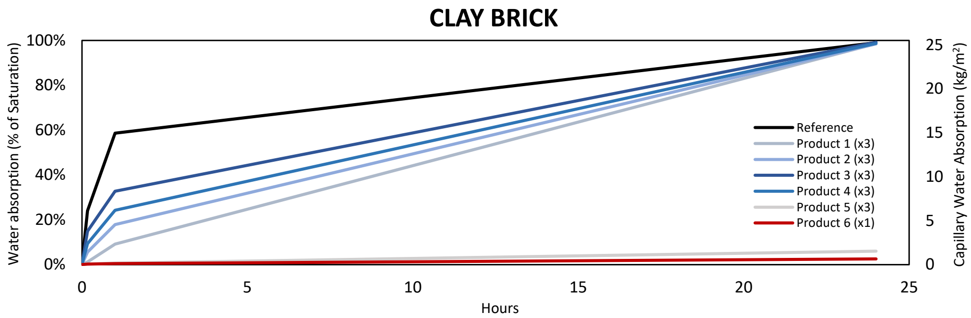

Figure 23. Water absorption (% and kg/m²) of clay brick for all the tested deep primers.

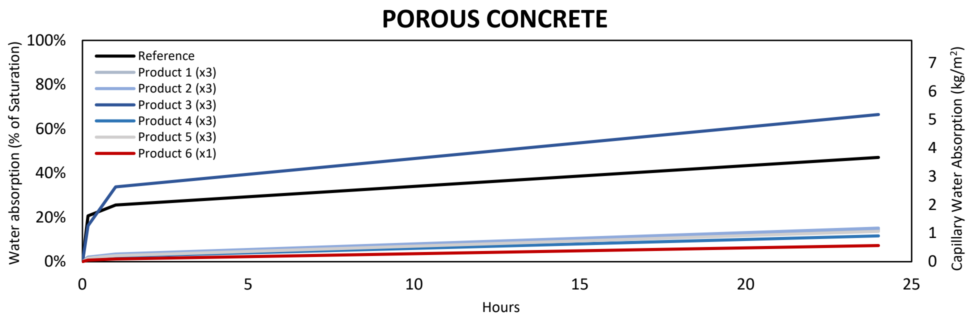

Figure 24. Water absorption (% and kg/m²) of porous concrete for all the tested deep primers.

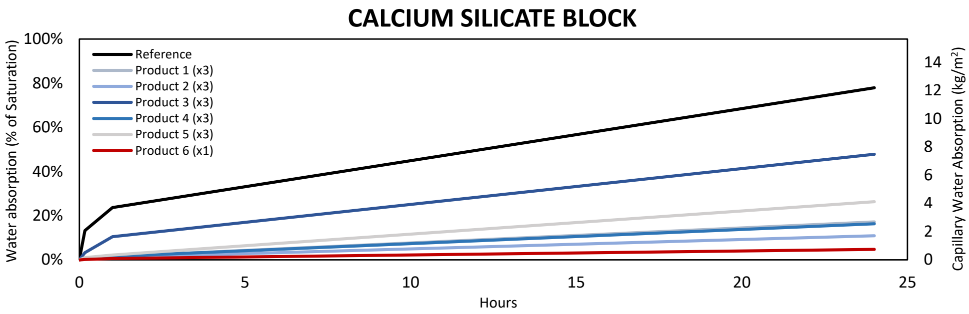

Figure 25. Water absorption (% and kg/m^2) of calcium silicate block for all the tested deep primers.

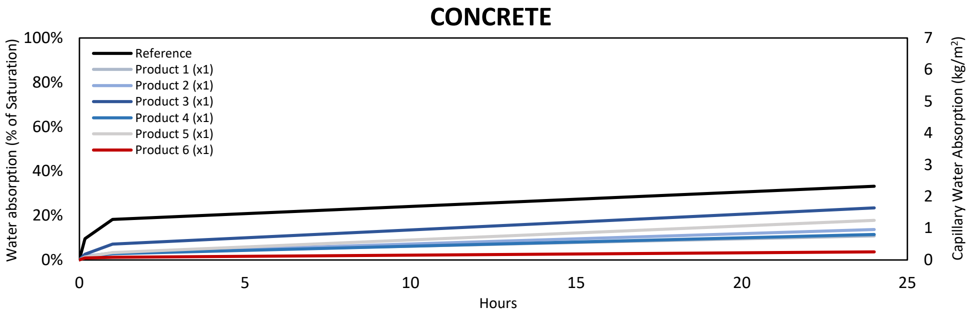

Figure 26. Water absorption (% and kg/m^2) of concrete for all the tested deep primers.

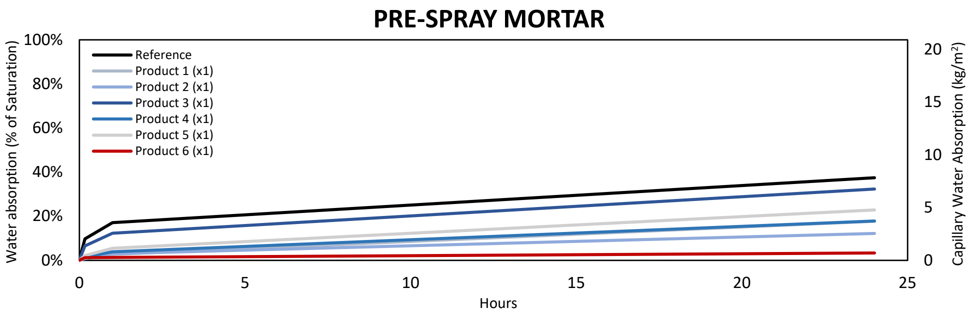

Figure 27. Water absorption (% and kg/m^2) of pre-spraying mortar for all the tested deep primers.

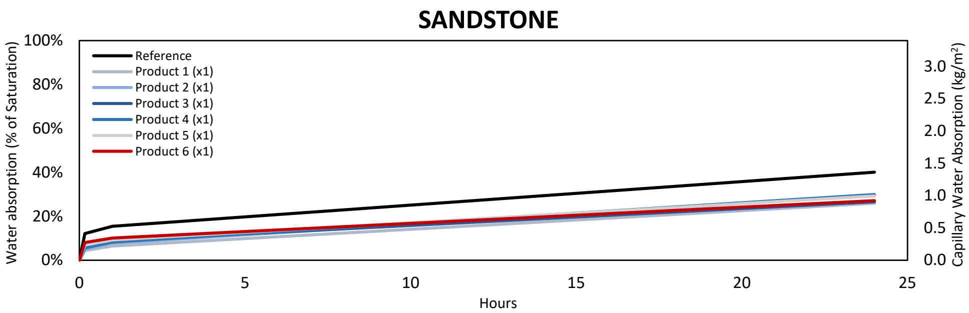

Figure 28. Water absorption (% and kg/m^2) of sandstone for all the tested deep primers.

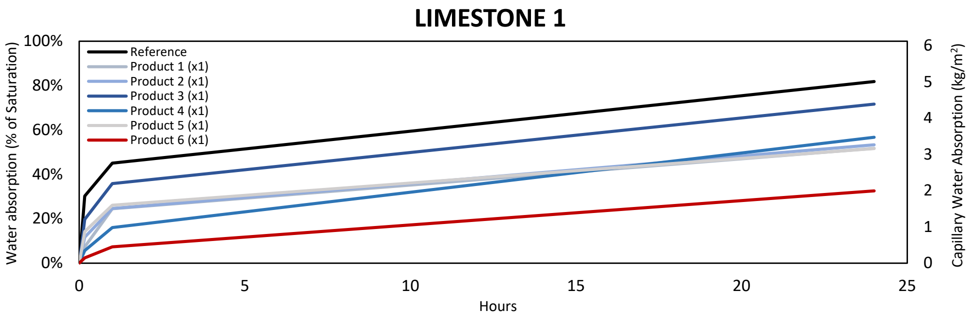

Figure 29. Water absorption (% and kg/m^2) of limestone 1 for all the tested deep primers.

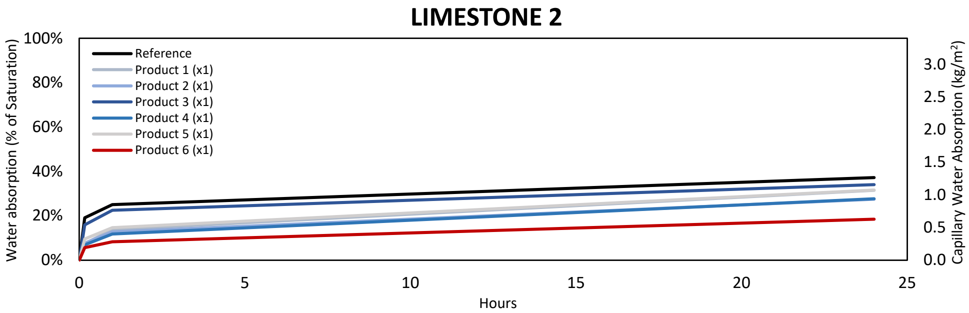

Figure 30. Water absorption (% and kg/m^2) of limestone 2 for all the tested deep primers.

The previous graphs shows that silicone-based water repellents, particularly from silanes/siloxanes are much more effective for reducing the capillary water absorption of mineral substrates, therefore, generating a hydrophobization effect. The latter is due the fact that they work by increasing the surface energy. This mechanism reduces the capillary action and increases the contact angle of the water droplets on the surface of the treated material. With this, they reduce the wetting of the surface, thus, reducing or preventing the water to penetrate the pore structure of the substrate, depending on the amount applied, but not affecting the vapour diffusion.

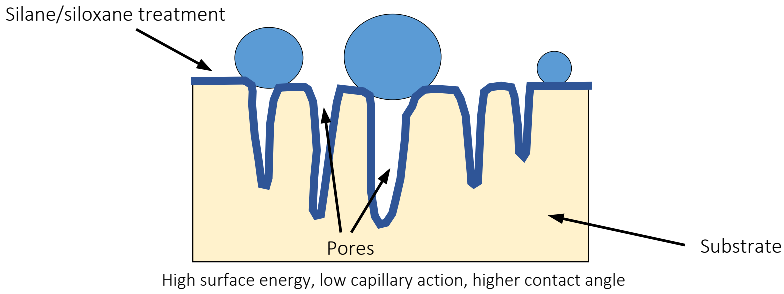

Figure 31. Schematic representation of the hydrophobized substrate in contact with water. Adapted from [7]

For the case of the substrates treated, the material is still able to be partially wetted, as only one application has been made. This is also beneficial for the application of the aerogel render, as it prevents the water sequestration from the latter, but still allowing a good bonding to the treated substrate.

WP3 (Modular wall for lab testing): The testing plates (porous concrete and clay brick) were made using the optimum coating found in the WP2 (Product 6 – silane based), whereas a pre-spraying mortar was applied before the application of the insulating renders:

[7] https://www.concrete.org/Portals/0/Files/PDF/Webinars/Silanes%20-%20Selley.pdf

Figure 32. Testing plates (brick and porous concrete). Left: Plates with hanging setup. Right: Plates with pre-spraying mortar and coating applied as well support for the application of 6 cm of insulating render.

To replicate the façade system, all the layers on the villa were also applied to the testing plates (insulating render, adhesive mortar, rough coating and mineral paint.

Figure 33. Left: Insulating render 1 begin applied. Right: Plates with adhesive mortar applied.

To perform the weathering of the testing plates, a wooden structure was built on-site, next to the façade. There the testing plates were placed for weathering of up to 12 months, taking four plates per render (8 plates in total) each month for testing mechanical properties.

Figure 34. Left: Wooden structure built for the testing plates. Right: Testing plates placed in the wooden structure.

For each of the 8 plates, compressive strength and pull-out tests are being performed:

Figure 35. Left: Picture of the compressive strength test. Right: Picture of the pull-out test.

Mechanical tests: The results of the compressive strength tests for the 12 months are presented in the following graph (Figure 26). As a comparison, tests were collected during the application and stored under lab conditions (20C), covering the samples with a plastic foil for 7 days, 28 days and 3 months. Once achieving the targeted age, the samples were dried and tested in order to obtain the comparative results. The samples from the testing plates were not conditioned (% of humidity was kept as from the on-site testing wall). This will allow in an advanced stage, the assessment of the influence of drying in the mechanical properties on each render.

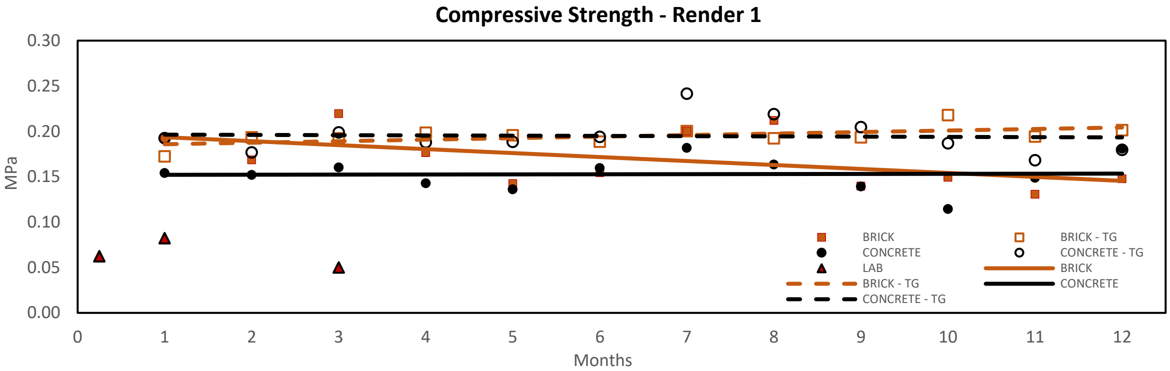

Figure 36. Results of the compressive strength test of Render 1.

In the previous figure it can be observed the fully dried samples of the render 1 presented a much lower compressive strength compared to the samples from the on-site testing wall. This can be explained due to the fact that the on-site environment provides carbonation to the samples, required to achieve higher mechanical properties in binders with high lime content. In fact, the samples in the lab were not conditioned to promote carbonation, but only curing with high relative humidity during the testing period. The results for the render 2 are:

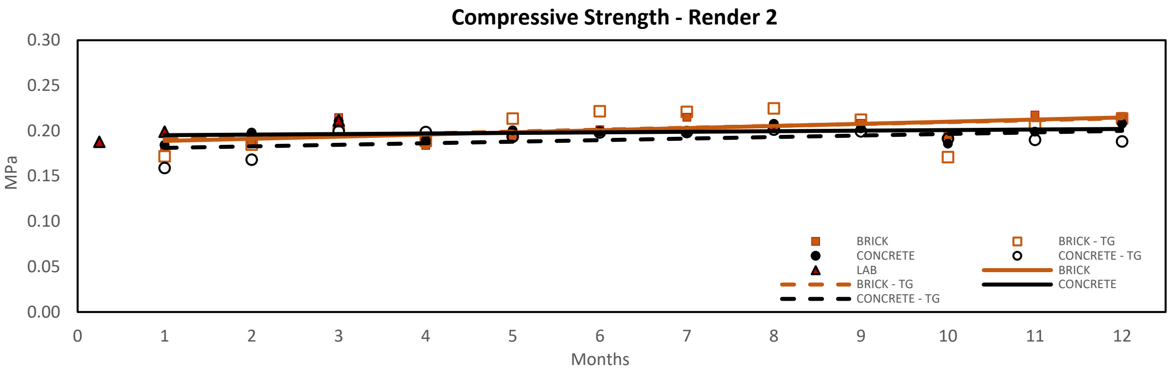

Figure 37. Results of the compressive strength test of Render 2.

As can be observed in the previous figure and in contrast to the render 1, the render 2 did not presented an influence of the drying in the compressive strength. In any case, both renders have differences in properties and conditions that influence the compressive strength and overall mechanical properties. However, in both cases, the mechanical properties are enhanced by the use of the coating, promoting a better curing.

Moreover, the bonding of the render was tested, assessing the bonding to the plate (pre-spraying mortar) and the adhesive mortar on the opposite side. The results on the bonding of the render 1 to the plate (pre-spraying mortar) and the adhesive mortar, as well as the influence of the deep primer (TG) are presented as follows:

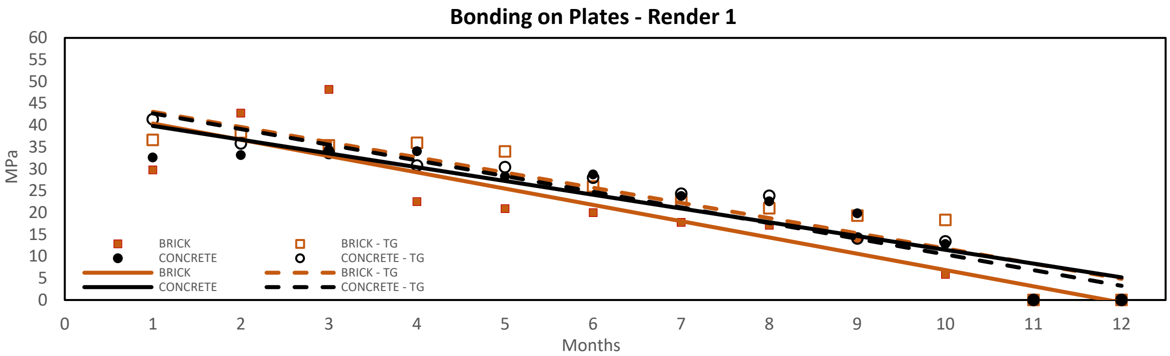

Figure 38. Results of the pull-out test on the plates of Render 1.

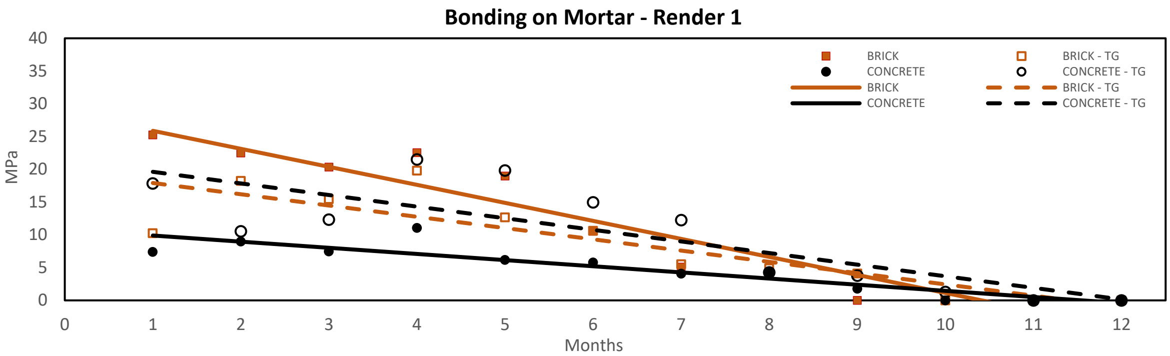

Figure 39. Results of the pull-out test on the adhesive mortar of Render 1.

The results on the bonding of the render 2 to the plate (pre-spraying mortar) and the adhesive mortar, as well as the influence of the deep primer (TG) are presented as follows:

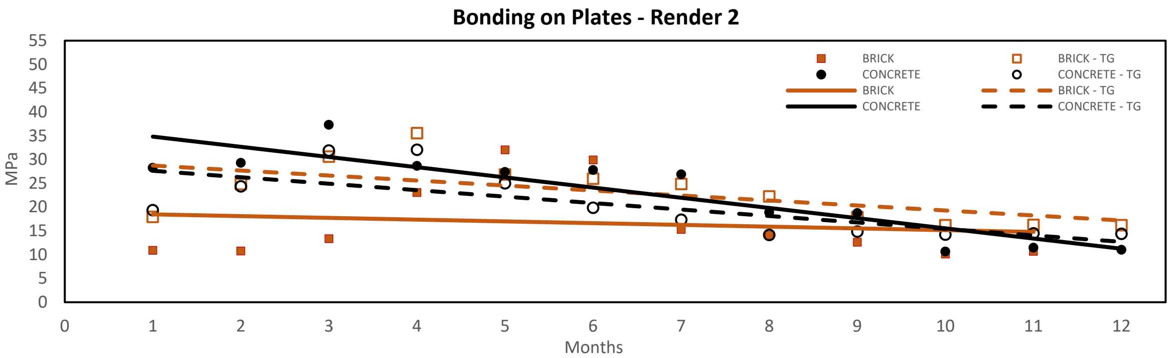

Figure 40. Results of the pull-out test on the plates of Render 2.

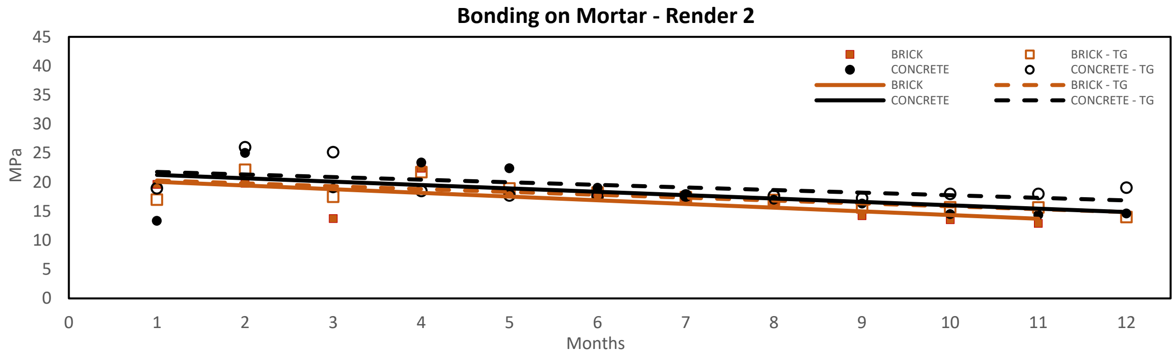

Figure 41. Results of the pull-out test on the adhesive mortar of Render 2.

It has been found that there is a correlation between the loss of bonding strength and the drying of the samples as can be observed below:

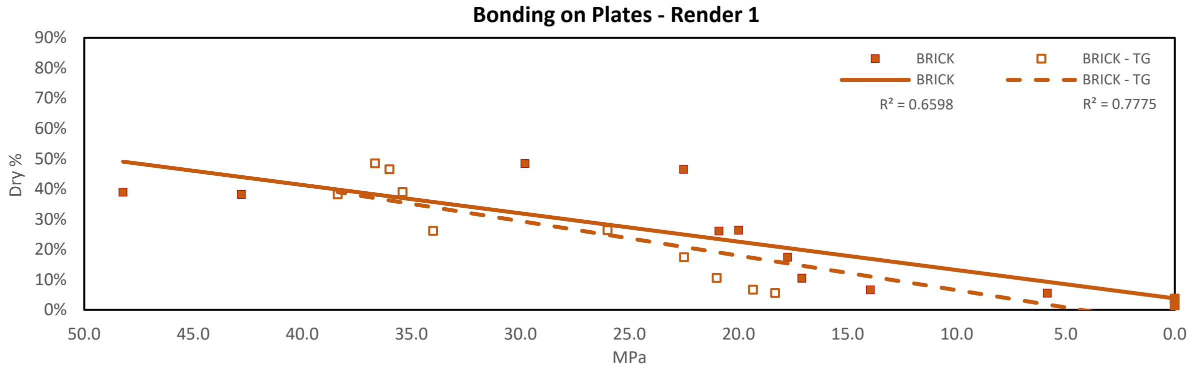

Figure 42. Correlation between bonding strength and drying percentage of Render 1 on Brick and treated Brick.

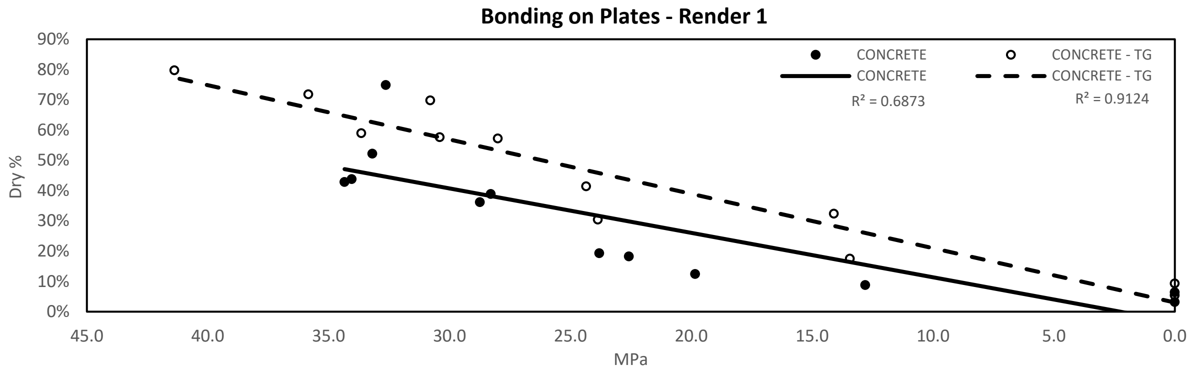

Figure 43. Correlation between bonding strength and drying percentage of Render 1 on Concrete and treated Concrete.

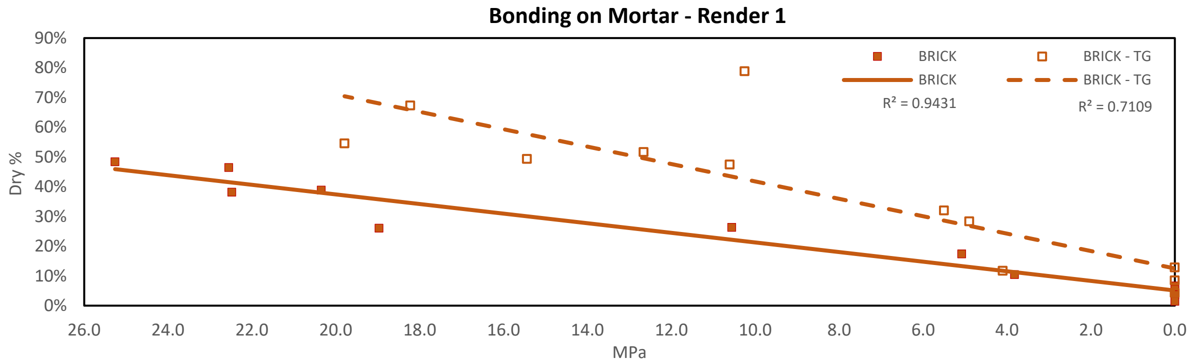

Figure 44. Correlation between bonding strength and drying percentage of Render 1 on Brick and treated Brick.

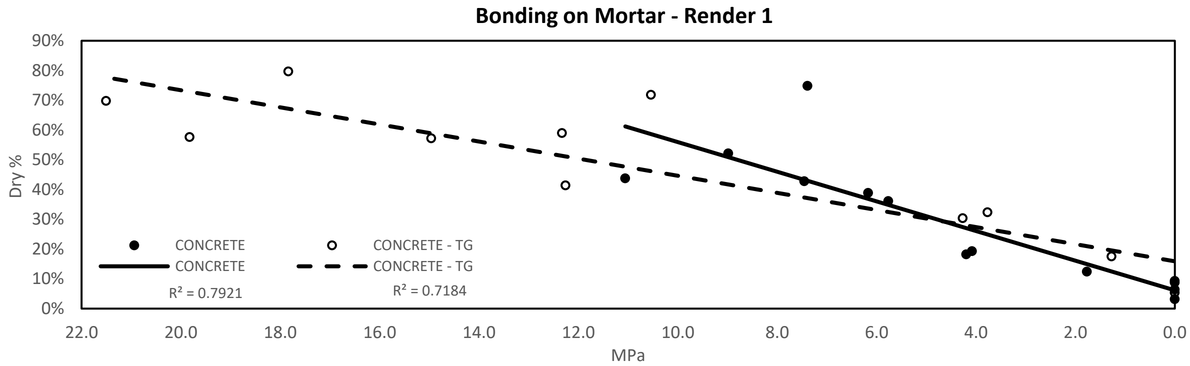

Figure 45. Correlation between bonding strength and drying percentage of Render 1 on Concrete and treated Concrete.

The previous graphs show the there is a correlation between the drying of the render 1 and the loss of bonding strength. This is due to the fact that the render 1 has a high shrinkage over time (drying shrinkage), which generate detachment and cracking of the aerogel render from the substrate until is completely de-bonded. In this case, the treated surface slows down the effect, however, it cannot avoid it. Nevertheless, the proposed system with anchors from the reinforced mesh/adhesive mortar overcomes this situation and can improve the durability and robustness to the façade system, despite the loss of bonding of the aerogel render.

The same correlation for the render 2 is presented below:

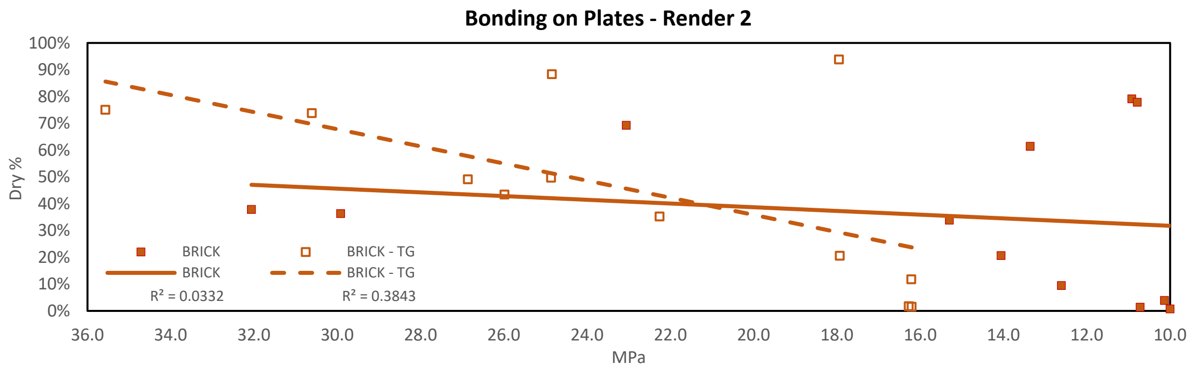

Figure 46. Correlation between bonding strength and drying percentage of Render 2 on Brick and treated Brick.

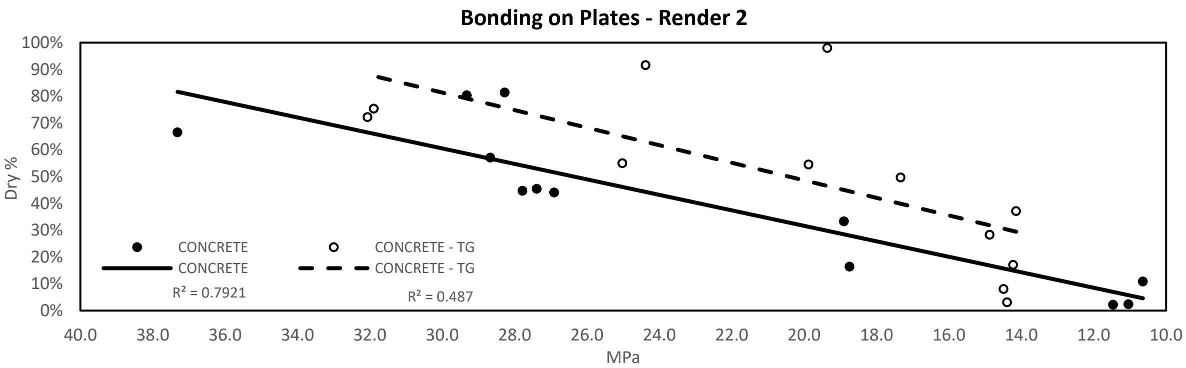

Figure 47. Correlation between bonding strength and drying percentage of Render 2 on Concrete and treated Concrete.

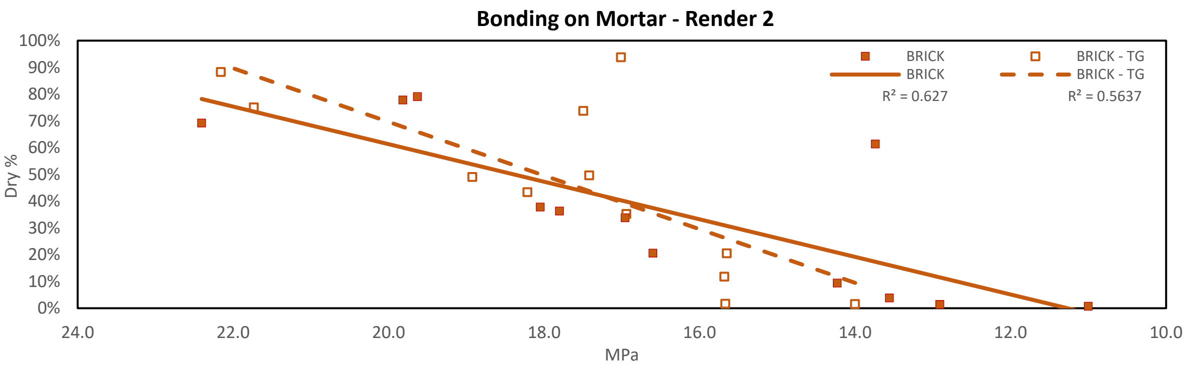

Figure 48. Correlation between bonding strength and drying percentage of Render 2 on Brick and treated Brick.

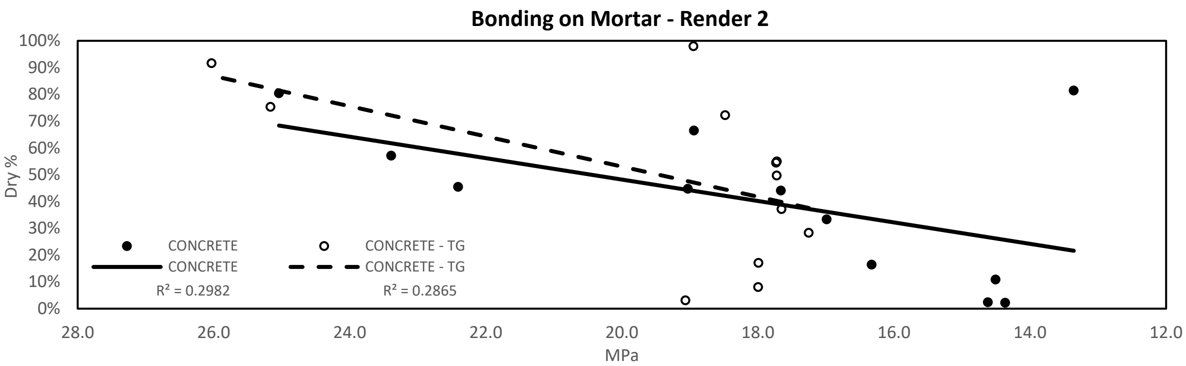

Figure 49. Correlation between bonding strength and drying percentage of Render 2 on Concrete and treated Concrete.

The previous graphs in regards to the render 2 however does not show such a clear correlation of a decreasing bonding with the drying of the aerogel render, as the loss of bonding strength only occurs partially. In fact, in can be observed a slight increase in the bonding for some samples from the first 3 months, when the hydration of the mineral binder is increasing. Moreover, as has shown earlier, during this three first months, the shrinkage is highly reduced with proper curing and the amount of water within the render is partially kept, as occurring with slow drying. Nevertheless, in the demonstrator the robustness is highly increased by the application of the anchor system proposed, eliminating any risk of detachment of the insulation system from the façade, as occurred in the render 1.

Degree of Hydration (DoH) tests: The samples for the 12 months, the samples stored in the lab for 7, 28 days and 3 months were classified by the different temperature ranges and the weight loss for the evolution of the mineral phases for de-hydration from 105C to 440C.The data of the renders are presented in Table 05 and 06:

Table 05. Degree of Hydration (DoH) of render 1 by TGA.

Render 1: Sample	Ldh (105C-440C) - Weight loss	DoH (%)
Hydrated	8.10	100%
Lab 7D	4.74	58%
Lab 28D	4.91	61%
Lab 3M	5.83	72%
Oct 2021 (Brick)	6.11	75%
Oct 2021 (Brick-TG)	6.40	79%
Oct 2021 (Concrete)	6.02	74%
Oct 2021 (Concrete-TG)	6.66	82%
Nov 2021 (Brick)	6.01	74%
Nov 2021 (Brick-TG)	6.49	80%
Nov 2021 (Concrete)	6.30	78%
Nov 2021 (Concrete-TG)	6.72	83%
Dec 2021 (Brick)	7.15	88%
Dec 2021 (Brick-TG)	7.50	93%
Dec 2021 (Concrete)	6.61	82%
Dec 2021 (Concrete-TG)	7.62	94%
Jan 2022 (Brick)	6.75	83%
Jan 2022 (Brick-TG)	7.02	87%
Jan 2022 (Concrete)	6.27	77%
Jan 2022 (Concrete-TG)	7.29	90%
Feb 2022 (Brick)	6.19	76%
Feb 2022 (Brick-TG)	7.18	89%
Feb 2022 (Concrete)	6.52	80%
Feb 2022 (Concrete-TG)	7.10	88%
Mar 2022 (Brick)	6.63	82%
Mar 2022 (Brick-TG)	7.21	89%
Mar 2022 (Concrete)	6.82	84%
Mar 2022 (Concrete-TG)	7.34	91%
Apr 2022 (Brick)	6.10	75%
Apr 2022 (Brick-TG)	7.62	94%
Apr 2022 (Concrete)	6.85	85%
Apr 2022 (Concrete-TG)	7.67	95%
May 2022 (Brick)	6.58	81%
May 2022 (Brick-TG)	7.62	94%
May 2022 (Concrete)	6.85	85%
May 2022 (Concrete-TG)	7.67	95%
Jun 2022 (Brick)	5.76	71%

Jun 2022 (Brick-TG)	7.32	90%
Jun 2022 (Concrete)	7.05	87%
Jun 2022 (Concrete-TG)	7.65	95%
Jul 2022 (Brick)	6.80	84%
Jul 2022 (Brick-TG)	7.45	92%
Jul 2022 (Concrete)	7.46	92%
Jul 2022 (Concrete-TG)	6.11	75%
Ago 2022 (Brick)	6.11	75%
Ago 2022 (Brick-TG)	6.87	85%
Ago 2022 (Concrete)	6.34	78%
Ago 2022 (Concrete-TG)	6.85	85%
Sep 2022 (Brick)	7.05	87%
Sep 2022 (Brick-TG)	7.46	92%
Sep 2022 (Concrete)	6.42	79%
Sep 2022 (Concrete-TG)	7.58	94%

Ldh: Dehydration, DoH: Degree of hydration

Table 06. Degree of Hydration (DoH) of render 2 by TGA.

Render 2: Sample	Ldh (105C-440C): Weight loss	DoH (%)
Hydrated	5.60	100%
Lab 7D	4.50	80%
Lab 28D	4.91	85%
Lab 3M	5.00	89%
Oct 2021 (Brick)	4.59	82%
Oct 2021 (Brick-TG)	4.69	84%
Oct 2021 (Concrete)	4.20	75%
Oct 2021 (Concrete-TG)	5.20	93%
Nov 2021 (Brick)	4.58	82%
Nov 2021 (Brick-TG)	4.86	87%
Nov 2021 (Concrete)	4.65	83%
Nov 2021 (Concrete-TG)	4.90	87%
Dec 2021 (Brick)	4.74	85%
Dec 2021 (Brick-TG)	5.37	96%
Dec 2021 (Concrete)	4.83	86%
Dec 2021 (Concrete-TG)	4.78	85%
Jan 2022 (Brick)	4.97	89%
Jan 2022 (Brick-TG)	4.97	89%
Jan 2022 (Concrete)	4.92	88%
Jan 2022 (Concrete-TG)	4.51	81%
Feb 2022 (Brick)	4.54	81%
Feb 2022 (Brick-TG)	4.98	89%
Feb 2022 (Concrete)	4.60	82%
Feb 2022 (Concrete-TG)	4.59	82%

Mar 2022 (Brick)	4.45	79%
Mar 2022 (Brick-TG)	4.79	85%
Mar 2022 (Concrete)	4.89	87%
Mar 2022 (Concrete-TG)	5.20	93%
Apr 2022 (Brick)	5.03	90%
Apr 2022 (Brick-TG)	4.96	88%
Apr 2022 (Concrete)	4.96	89%
Apr 2022 (Concrete-TG)	5.10	91%
May 2022 (Brick)	4.49	80%
May 2022 (Brick-TG)	4.76	85%
May 2022 (Concrete)	4.85	87%
May 2022 (Concrete-TG)	4.88	87%
Jun 2022 (Brick)	5.18	93%
Jun 2022 (Brick-TG)	4.68	84%
Jun 2022 (Concrete)	4.79	85%
Jun 2022 (Concrete-TG)	4.91	88%
Jul 2022 (Brick)	5.09	91%
Jul 2022 (Brick-TG)	5.02	90%
Jul 2022 (Concrete)	5.20	93%
Jul 2022 (Concrete-TG)	5.07	90%
Ago 2022 (Brick)	4.89	87%
Ago 2022 (Brick-TG)	5.15	92%
Ago 2022 (Concrete)	4.78	85%
Ago 2022 (Concrete-TG)	5.12	91%
Sep 2022 (Brick)	4.78	85%
Sep 2022 (Brick-TG)	5.45	97%
Sep 2022 (Concrete)	4.45	79%
Sep 2022 (Concrete-TG)	5.25	94%

**Ldh: Dehydration, DoH: Degree of hydration*

The evolution of the Degree of Hydration for both renders is presented below:

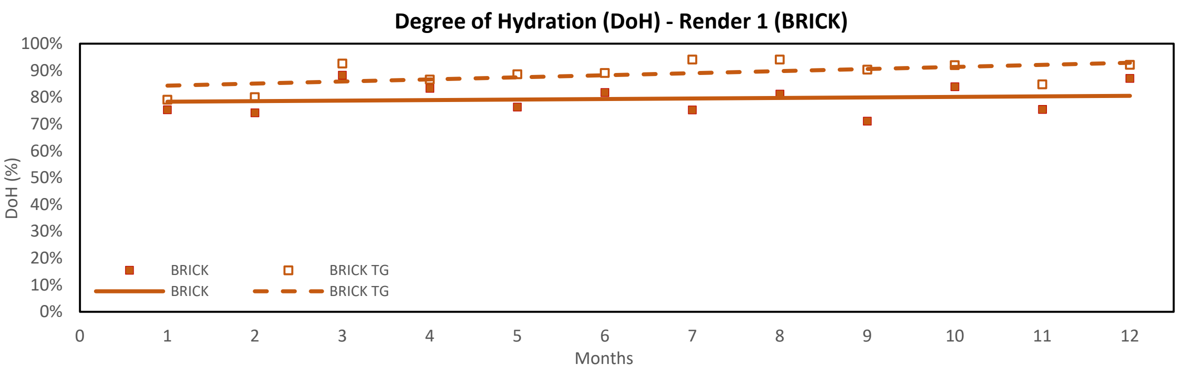

Figure 50. Evolution of Degree of Hydration of Render 1 on Brick and treated Brick.

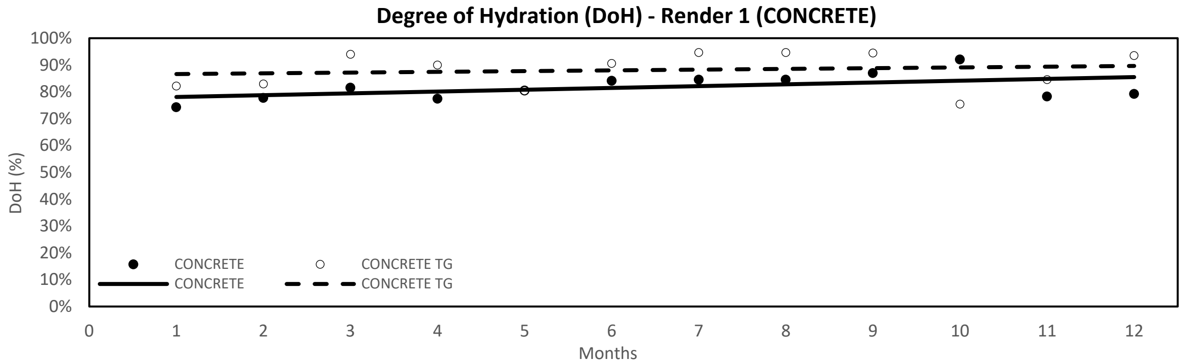

Figure 51. Evolution of Degree of Hydration of Render 1 on Concrete and treated Concrete.

The previous graphs shows that the mineral binder within the render 1 presented an increased tendency in terms of hydration. This was achieved due to the applied system before the render was dried, which provided a proper curing. This had a positive impact in the compressive strength of the render as shown in Figure 26. Moreover, the treatment applied to the substrates (Deep primer) also provided a positive impact in the Degree of Hydration, consistent with the improvement in the compressive strength as shown in Figure 36. This effect was visible in both brick and concrete substrates.

The graphs for the render 2 are presented below:

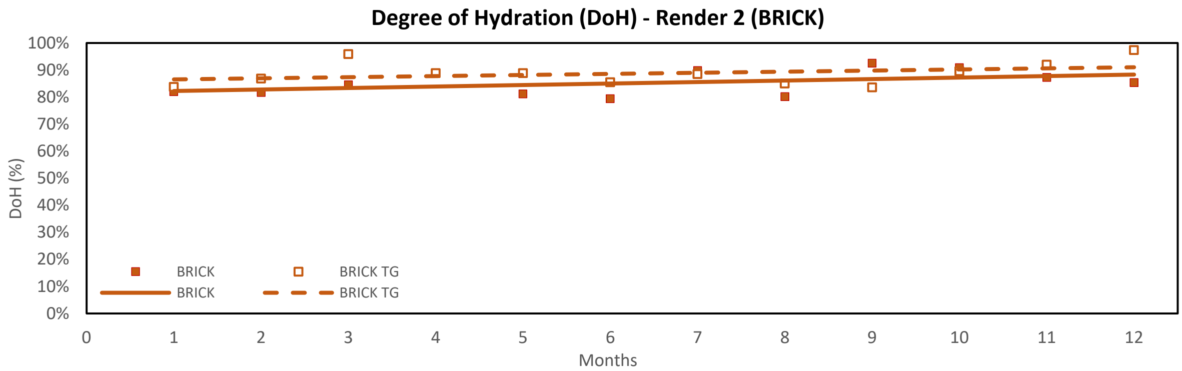

Figure 52. Evolution of Degree of Hydration of Render 2 on Brick and treated Brick.

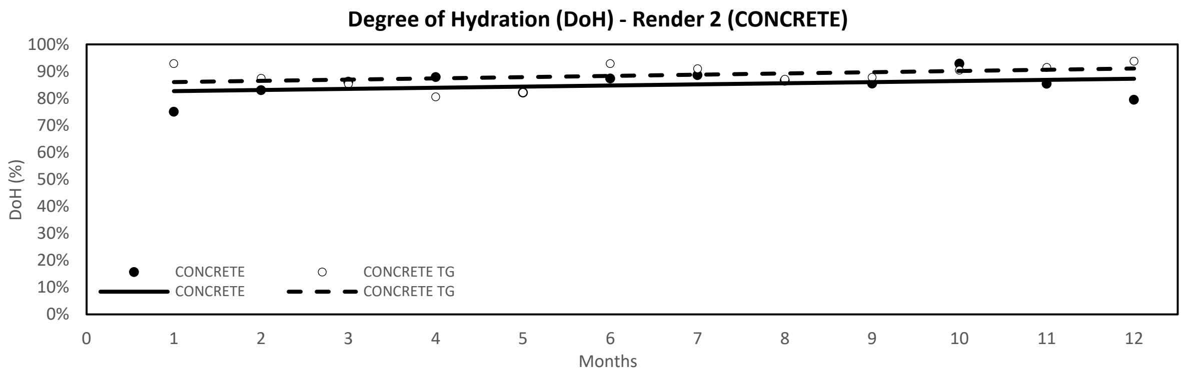

Figure 53. Evolution of Degree of Hydration of Render 2 on Concrete and treated Concrete.

The previous graphs also show the same positive effect in terms of Improvement in the degree of hydration for the render 2 as for the render 1, promoted by the coating on the substrates in both cases. Such effect is also consistent with the data for compressive strength of the render 2 presented in Figure 37.

Thermal conductivity tests: The results from the thermal conductivity tests at different ages are shown below:

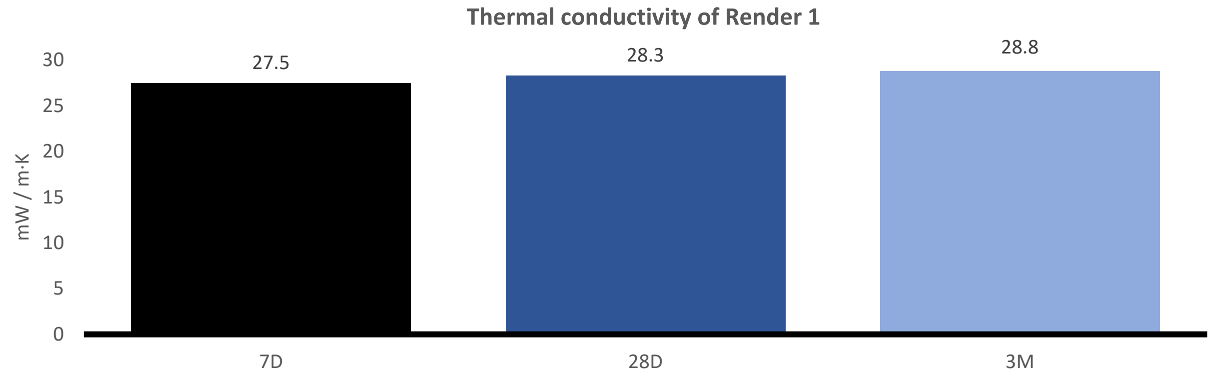

Figure 54. Results of the thermal conductivity tests of Render 1.

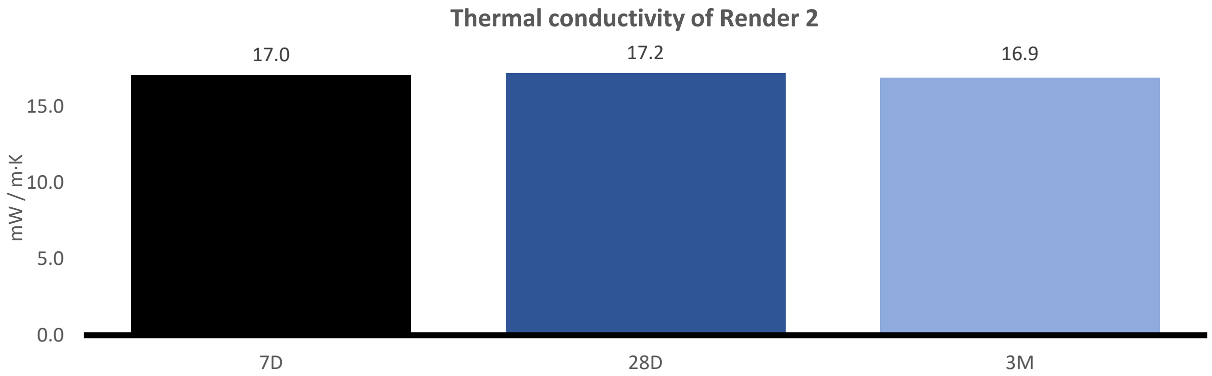

Figure 55. Results of the thermal conductivity tests of Render 2.

As shown in the previous graph, the thermal conductivity (thermal insulation capacity) of the applied render remained constant during the tests. Therefore, as for the mechanical properties, the thermal insulation from Aeroskin tech render is robust.

Shrinkage: The results from the shrinkage tests at different ages are shown below:

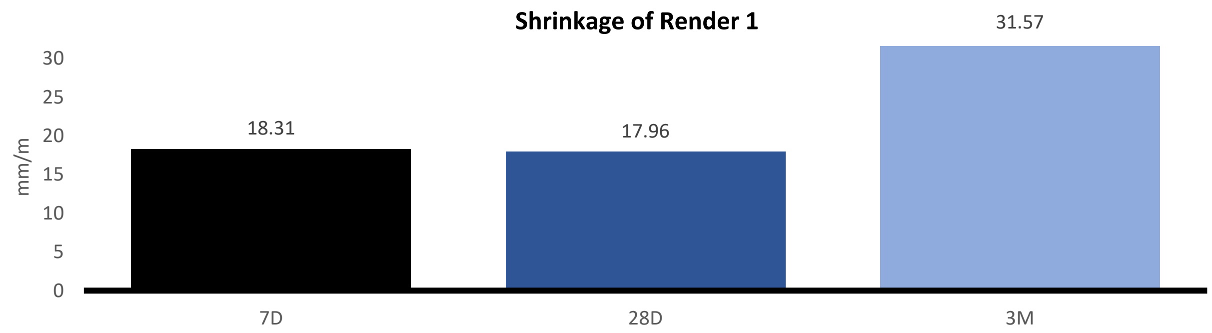

Figure 56. Results of shrinkage tests of Render 1.

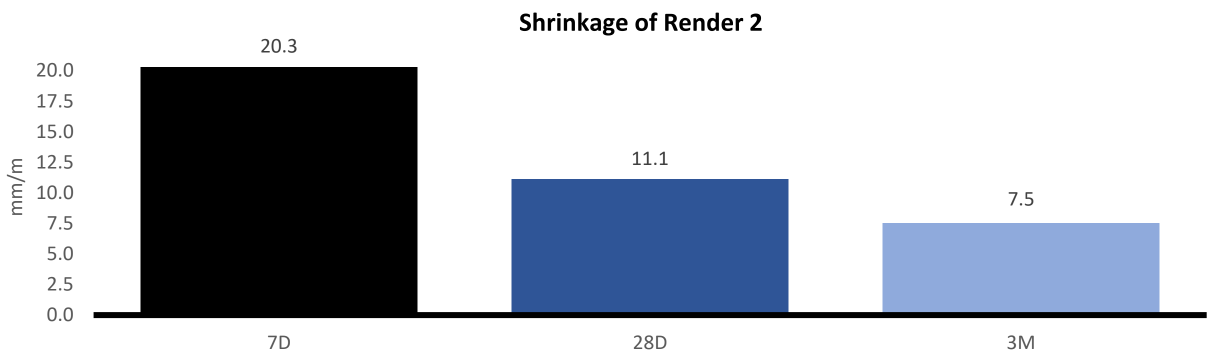

Figure 57. Results of shrinkage tests of Render 2.

As shown in the previous graph, the shrinkage of the material is reduced as the curing time is increased under lab conditions. Therefore, is quite suitable for the render to not have a drastic drying in early stages in order to reduce its shrinkage. In this sense, the applied render on the façade is in line with the mentioned material needs, as the protective and finishing layers prevent a fast drying, allowing longer curing times for the aerogel render within the façade. Nevertheless, each render has a different influence due to lack of carbonation. In particular, render 2 is more sensitive to lack of carbonation, not achieved in lab conditions. The latter explains in part, the differences in the evolution of the generated microstructure of the matrix, to which render 1 is not well developed compared to render 2. In fact, render 1 presented worse behaviour evolution in mechanical properties consistent with the high shrinkage on the material, affecting the internal bonding of the components and the matrix in general.

WP4: Villa in the mountain: The demonstration site consists in a mountain villa in Lenzerheide. The render 2 was applied to the façade as an External Thermal Insulation (ETICS). The construction process started with the excavation of a trench (Fig. 36, Left) on the perimeter in order to intervene also the concrete slabs' thermal bridge. In this sense, an adhesive bitumen was applied, to protect from water but also to bond the XPS plates (12 cm thickness). An average of 50 cm down to the earth was applied, including a second external layer of bitumen.

Figure 58. Left: Excavation of the trench around the villa for the application of XPS for breaking the thermal bridge. Right: Application of the pre-spray mortar on the façade.

For the façade, the first step was to clean it a place a plastic on the windows and areas that were no to be renovated. Then, a pre-spraying mortar was applied in order to generate a rough surface to promote a better bonding of the aerogel render (Fig 37, right). The pre-spraying mortar was let to harden and dry overnight. The next step was to apply 6 cm of aerogel render by spraying machine (render 2, Fig. 37, left), finishing the application with a smooth surface (Fig. 37, right).

Figure 59. Left: Application of the insulating render (2) on the façade. Right: View of the façade with the insulating render applied and the surface smoothen.

Once the application was done, a plastic foil (Fig. 38, right) was applied to the render to prevent water evaporation during hardening. Usually, this is performed by the scaffolding and plastic already in such cases, however, in this demonstrator, the scaffolding was not used as the application was only on the ground floor.

Figure 60. Left: View of the façade with the insulating render applied and the surface smoothen. Right: Plastic foil applied on the façade to prevent early drying during the hardening process.

The next day of the aerogel render application, an adhesive mortar with an embedded mesh was applied (Fig 39 and 40, left). The layer was left for hardening and drying for 10 days.

Figure 61. Left: Application of the adhesive mortar on top of the insulating render. Right: Application of the net embedded into the adhesive mortar.

To improve the bonding of the system and long-term robustness, mechanical fixations were applied (as used in ETICS based on insulating boards), followed by a second layer of adhesive mortar and mesh:

Figure 62. Left: Application of the anchor system.

The next layer applied was a rough coating (Fig. 40, right), leaving another week for hardening and drying.

Figure 63. Left: View of the façade with the adhesive mortar applied. Right: View of the villa with the rough coating applied.

Finally, a mineral silicate exterior paint was applied to obtain desired façade colour (Fig 41).

Figure 64. View of the final state of the renovated villa.

WP5: **Demonstrator's monitoring:** The monitoring of the drying evolution is being made via embedded sensors, applied on the inside of the room, the external surface of the façade and also on both sides of the applied aerogel render. In all cases, two sensors were installed:

Figure 65. Sensors applied to monitor humidity and temperature during 12 months.

The following graph shows the drying of the samples applied on concrete and brick substrates:

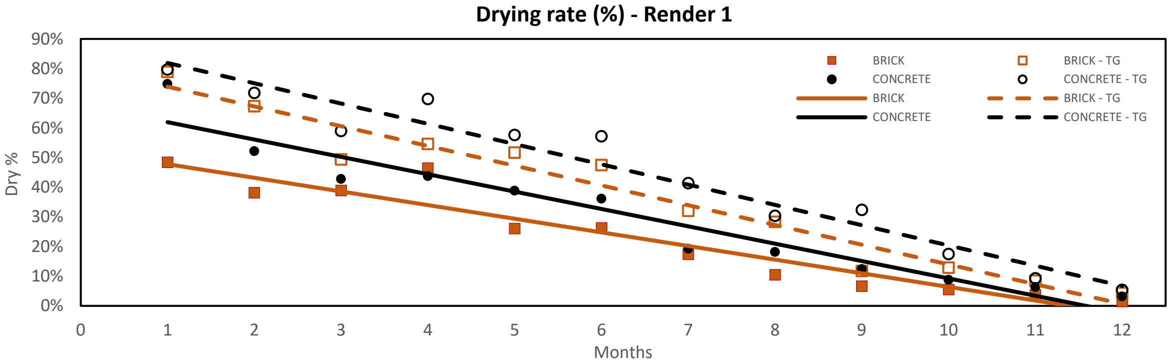

Figure 66. Results of Drying rate (%) of Render 1.

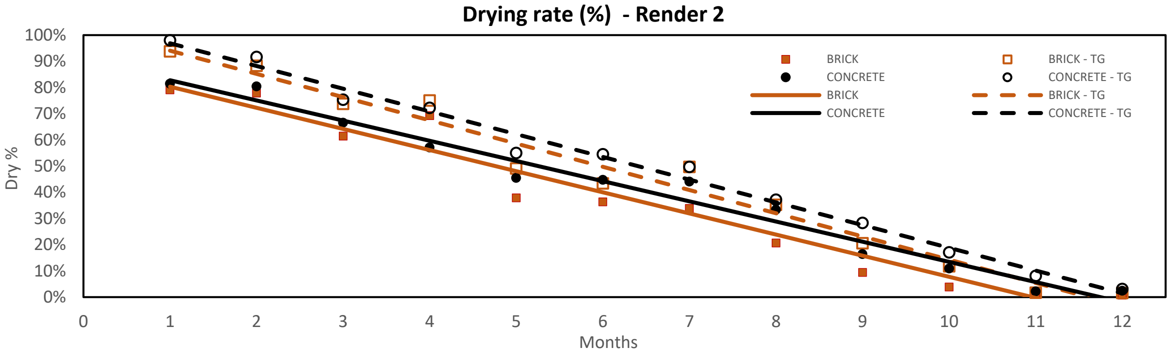

Figure 67. Results of Drying rate (%) of Render 2.

The previous graphs shows that the samples applied on brick substrates dried slightly faster, achieving a full dry state at around 11 months, instead of 12 months compared to the samples applied on concrete plates. The drying rate is related to the vapour diffusion coefficient of the covering layers (μ = 25), but also to the outdoor conditions (temperature and humidity in the environment). The temperature and relative humidity of the on-site conditions recorded by the sensors were as follows:

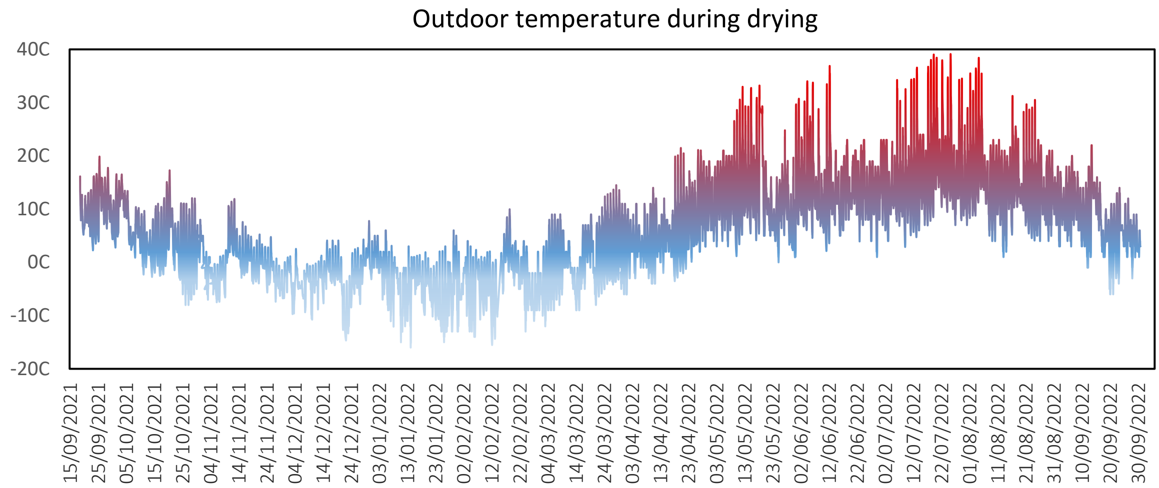

Figure 68. Outdoor temperature during drying.

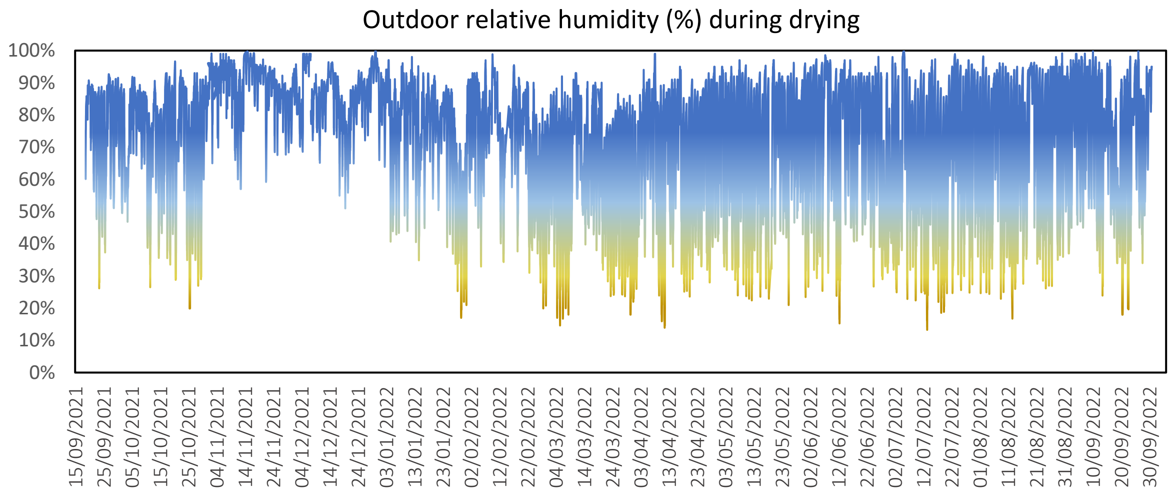

Figure 69. Outdoor relative humidity during drying.

The colours of the temperature graph (first) represent the temperature, whereas red means hot temperatures, blue low temperatures and light blue, freezing temperatures respectively. For the humidity graph (second), the colours represent the amount of humidity of the environment, from blue (humid) to brown (dry) respectively. Moreover, the previous graphs show that the façade system was exposed during drying to severe conditions without any negative side effects. In fact, already at around 1 month of application, the temperatures were already below 0 degC during the night. On the other hand, the weather conditions also included a very broad range of relative humidities, however, in most of the cases, the relative humidity was quite high, not promoting a fast drying overall. Nevertheless, the study shows that the render ended in a fully dry state condition, therefore, not having any negative influence on the thermal insulation capacity of the material.

Fully dry monitoring and vapour diffusion tests (Render 2):

In regards to the fully dry monitoring, the assessment consisted in monitoring the vapour diffusion through the façade, by monitoring the temperature and relative humidity indoor, outdoor and on the outer side of the aerogel render, between the render and the external protective layers (External Thermal Insulation System described in WP2). Example of the sensors' setup presented above. The experimental setup of the above-mentioned sensors was complemented by vapour diffusion coefficient tests performed to samples taken from the WP2-WP3, by the wet cup test (European Standard EN-1015-19:2005). The results of the monitored temperature and relative humidity are presented below:

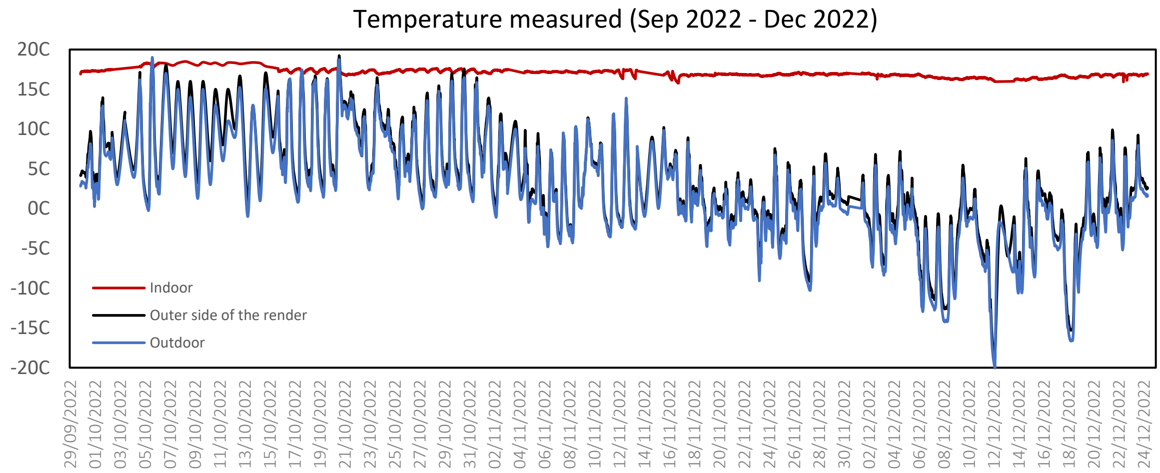

Figure 70. Temperature during monitoring (Sep – 2022 – Dec 2022) for the different sensors.

The temperature sensors showed a constant indoor temperature. On the other hand, the outdoor sensors and the sensors placed on the outer side of the render were quite similar, only slightly shifted. This is consistent with the small thickness and the relatively high thermal conductivity of the outer protective layers, which transfer the heat very efficiently (not a thermal insulator).

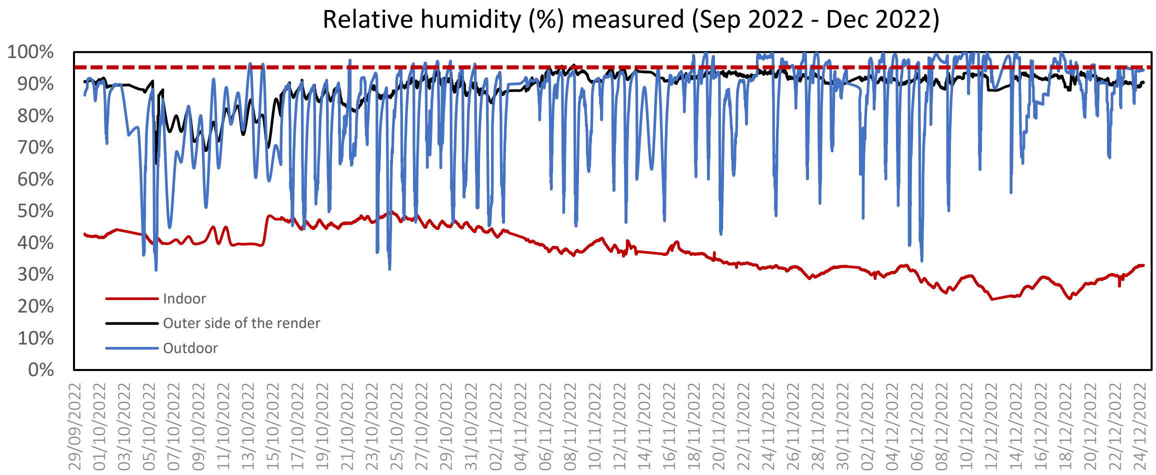

Figure 71. Relative humidity during monitoring (Sep – 2022 – Dec 2022) for the different sensors.

In contrast to the temperature sensors, the relative humidity measured showed a lower relative humidity indoor. Moreover, the outdoor relative humidity increases with the temperature decrease and vice versa. Nevertheless, the humidity on the outer side of the render is also related to the humidity migration from the inside of the building. However, the results showed that there was no condensation on such layer (<95%, below the red dotted line), due to the very high vapor diffusion capacity of the render, whereas, there is a slight accumulation on such interface due to the slightly lower vapor diffusion capacity of the protective layers (μ = 25).

To have a better assessment of the risk of condensation of system applied to the demonstrator, the tests were complemented with vapor diffusion tests to the render 2. The results are showed below:

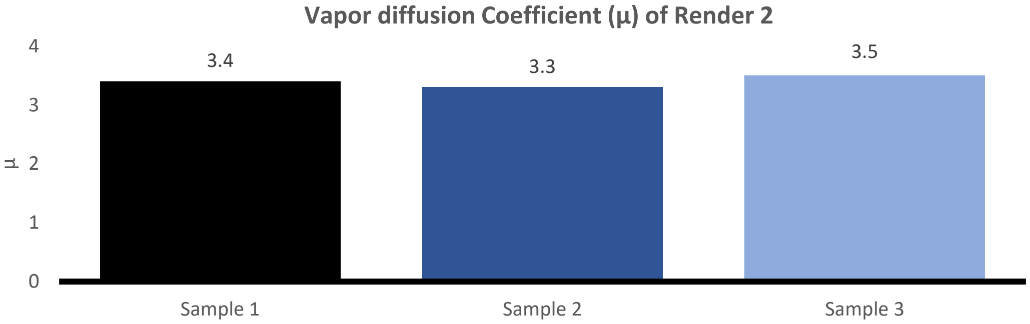

Figure 72. Vapor diffusion Coefficient (µ) of Render 2.

The previous graph shows that the render 2 is open to vapor diffusion (µ ~ 4). Moreover, it general thermo-hygric behaviour integrated into the installed ETICS is shown below:

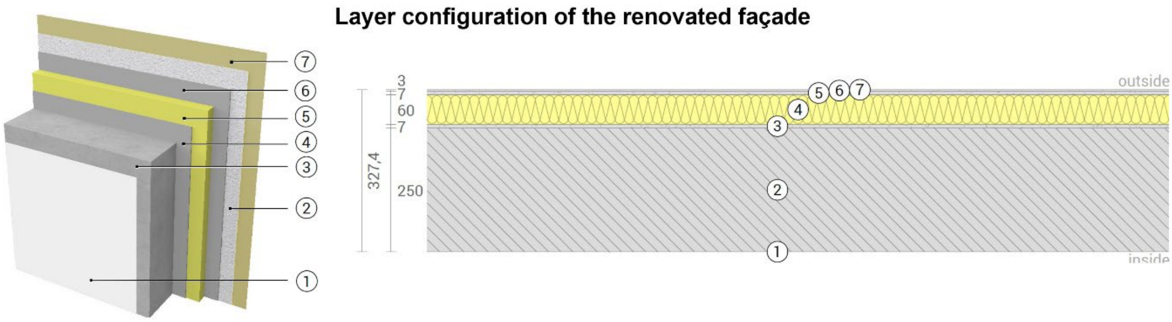

Figure 72. Layer configuration of ETICS (Render 2) installed on the façade.

Table 07. U-value and layer configuration of the façade.

Layer	Material	Thickness (cm)	λ (W/mK)	R (m^2K/W)	µ
	Thermal resistance inside (Rsi)			0.130	-
1	Indoor paint	0.02	0.600	0.000	900
2	Concrete 1800kg/m³	25.00	1.150	0.217	60
3	Rajasil SPB (spritzbewurf)	0.70	0.440	0.016	20
4	Render 2	6.00	0.017	3.529	4
5	MultiThermAero K+A	0.70	0.870	0.008	25
6	HECK SHP (Siliconharzputz)	0.30	0.890	0.003	50
7	Rajasil SHF (siliconharzfarbe)	0.02	0.500	0.000	25
	Thermal resistance outside (Rse)			0.040	-
			R tot =	3.945	
			U value =	0.25 W/m^2K	

As can be observed, the U-value reached is 0.25, considering all the layers of the wall. Moreover, the thermal gradient (temperature profile), humidity and moisture and vapour diffusion of the ETICS are shown below:

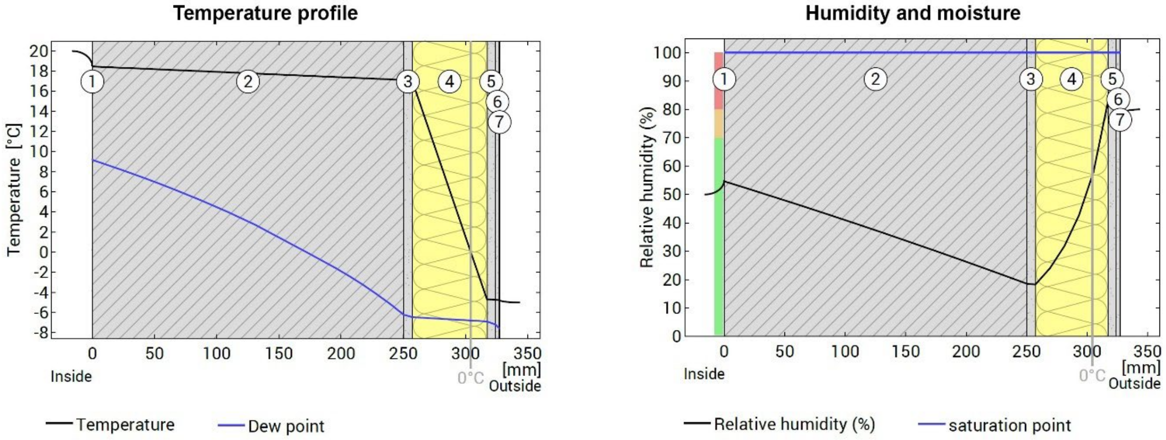

Figure 73. Temperature profile of ETICS (Render 2) installed on the façade.

The previous graphs show that the relative humidity of all layers is always below 95%. Moreover, the saturation pressure in both winter and summer is also not reached, thus, not generating condensations:

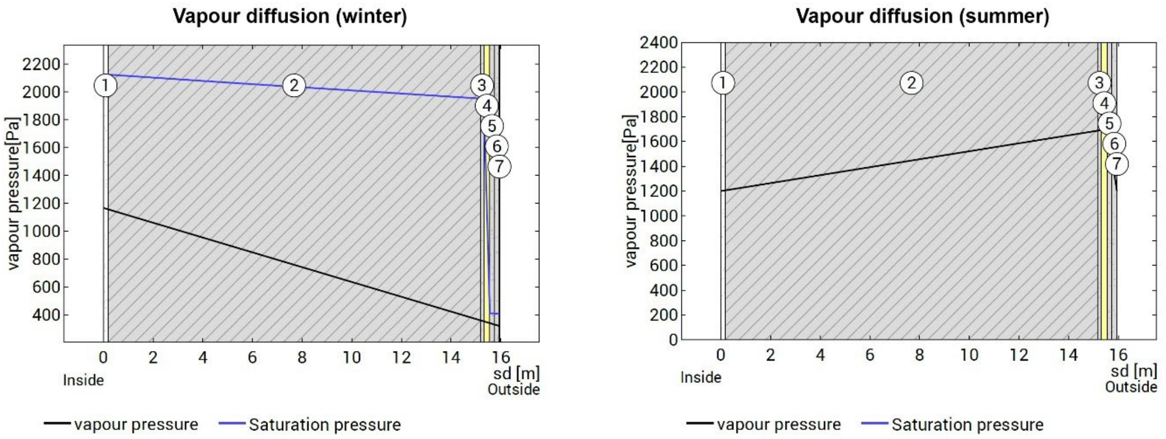

Figure 73. Vapour behaviour of ETICS (Render 2) installed on the façade.

As showed above, the render 2 is suitable for External Thermal Insulation Systems, risk-free from interstitial condensations. Nevertheless, an indoor application of the render would require a vapor barrier on the inner side of the insulation to also comply to the hygrothermal requirements of such type of applications.

WP6: Cost analysis: The cost for energy retrofit for façades in Switzerland based in the study performed in this project is dived in two main groups. Renovation using Insulation boards and Insulation based in insulating renders. The main costs implied in the intervention for ETICS using insulating boards are divided as follows:

Table 08. Cost distribution for energy retrofit of façades in Switzerland for insulating boards (ETICS).

Cost description	CHF/m^2
Preliminary work	60
Installation construction site	20
Scaffolding mounting and dismantling	20
Environment works	20
Preparatory work on the substrate/wall	30

Peeling off existing plaster	20
Clean / prepare substrate	5
Base coat	5
Main work for the installation of ETICS	60 - 128
Materials: ETICS system layers (besides the insulation)	40 - 45
Materials: Thermal insulation	According to product/thickness
Window reveals	0 - 60
Connections and terminations	40 - 80
Work on the surface (finishing)	40
Basic plaster middle layer	20
Paint	20

The previous graph shows a typical cost between 270 and 388 CHF/m^2 (not considering the insulating material), depending on the complexity of the building, giving an average cost of 326 CHF/m^2 for an ETICS system, plus the cost of the insulation itself. Nevertheless, traditional insulation will typically include between 30 – 60 CHF/m^2 in regards to the work on window reveals, with an average of 45 CHF/m^2, due to the thicker layer. Additionally, the connections and terminations also play role on the final man labour costs, depending on the complexity of the work. The following table summarizes the cost:

Table 09. Cost summary for energy retrofit of façades in Switzerland for insulating boards (ETICS).

Cost description	CHF/m^2
Man labour	220 - 328
Materials: Thermal insulation	According to product/thickness
Other materials and scaffolding	50 - 55

The main costs implied in the intervention for ETICS using insulating renders are divided as follows:

Table 10. Cost distribution for energy retrofit of façades in Switzerland for insulating renders (ETICS).

Cost description	CHF/m^2
Preliminary work	60
Installation construction site	20
Scaffolding mounting and dismantling	20
Environment works	20
Preparatory work on the substrate/wall	30
Peeling off existing plaster	20
Clean / prepare substrate	5
Base coat	5
Main work for the installation of ETICS	40 – 94 (3 - 11 cm applied)
Materials: ETICS system layers (besides the insulation)	31 - 35
Materials: Thermal insulation	According to product/thickness
Window reveals	0 - 60
Connections and terminations	40 - 80
Work on the surface (finishing)	20
Paint	20

The previous graph shows a typical cost between 200 and 325 CHF/m^2 (not considering the insulating material), depending on the complexity of the building, plus the cost of the insulation itself. Nevertheless, renders with similar performance to traditional insulation will typically include between 30 – 60 CHF/m^2 in regards to the work on window reveals, with an average of 45 CHF/m^2, due to the thicker layer. Also, the connections and termination have an impact in the final man labour price depending on the complexity of the work, as for insulating boards. Therefore, for a U-value of 0.25, such renders would cost between 256 and 319 CHF/m^2, (average of 288 CHF/m^2). Additionally, for a U-value of 0.20 (for subsidies), between 266 and 325 CHF/m^2 (average of 296 CHF/m^2). Not considering the insulation material in both cases.

On the other hand, aerogel renders with a similar performance to aerogel boards are estimated with a cost between 200 and 231 CHF/m^2 (average of 216 CHF/m^2) for a U-value of 0.25 and between 220 and 240 CHF/m^2 (average of 230 CHF/m^2) for a U-value of 0.20. In both cases without considering the cost of the insulation itself. The lower cost is explained due to the fact that the application is faster (less thickness) and no required work would be required on window reveals. The following table summarizes the cost:

Table 11. Cost summary for energy retrofit of façades in Switzerland for insulating renders (ETICS).

Cost description	CHF/m^2
Man labour	155 - 284
Materials: Thermal insulation	According to product/thickness
Other materials and scaffolding	41 - 45

In summary, the results are in line with industry standards in general, however, costs for window reveals, details, connections and terminations are usually not included in pre-work budget estimation, as it always depends on the building. Therefore, the cost estimation provided is more realistic, showing also the typical complexity ranges and derived costs for each type of application for boards and renders.

Free online price simulator: The results from this project are available for using for free as an online tool. In this sense, an online price simulator has been developed to get a price estimation of energy retrofit of façades using aerogel compared to traditional insulation. The tool is very simple and straight forward, in which only façade surface (total m^2) and percentage in glazing is required. Additionally, the user can select between the SIA regulation's U-valued to comply: U-value 0.25 (as for renovations) and 0.20 (as new building) to obtain subsidies. The results page gives the user a price range of the total renovation cost in Switzerland, for four aerogel products (Spaceloft, Pureflex and two aerogel renders) as well as for the four most used traditional insulation material (EPS, XPS, PIR and Mineral wool) with up-to-date typical market prices for every product. The URL is:

www.swissaerogel.ch

To illustrate the results from the online tool, a calculation for 100 m^2, with a U-value of 0.25 and glazing of 30% is presented below:

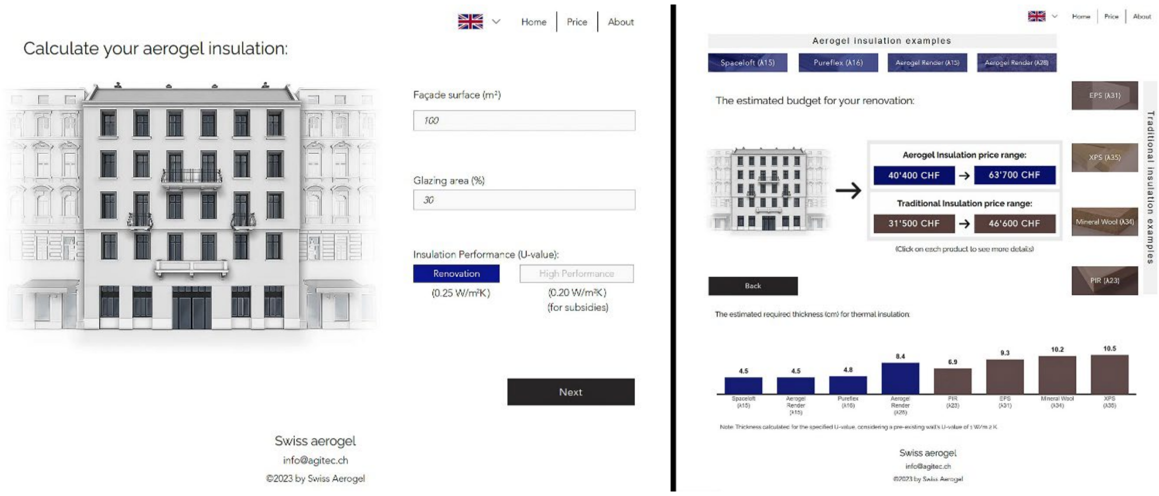

Figure 74. Online tool with inserted parameters and general results.

The results show the price range in blue for aerogel products, from 40k CHF up to 64k CHF, and for traditional insulation in brown, from 32k CHF up to 47k CHF, showing already an overlapping between both categories. Moreover, a thickness comparison for each solution is presented in a graph at the bottom of the page. Additionally, each solution is presented individually by clicking on each product's name tag:

Figure 75. Results for aerogel products from the online tool.

The previous images show the prices for each aerogel product. Note that the thermal conductivity of the high-performance aerogel render used is 15 mW/mK, as it shows the full potential of the material vs. the volumes market, being also a target to achieve for Aeroskin Tech. The traditional products are shown below:

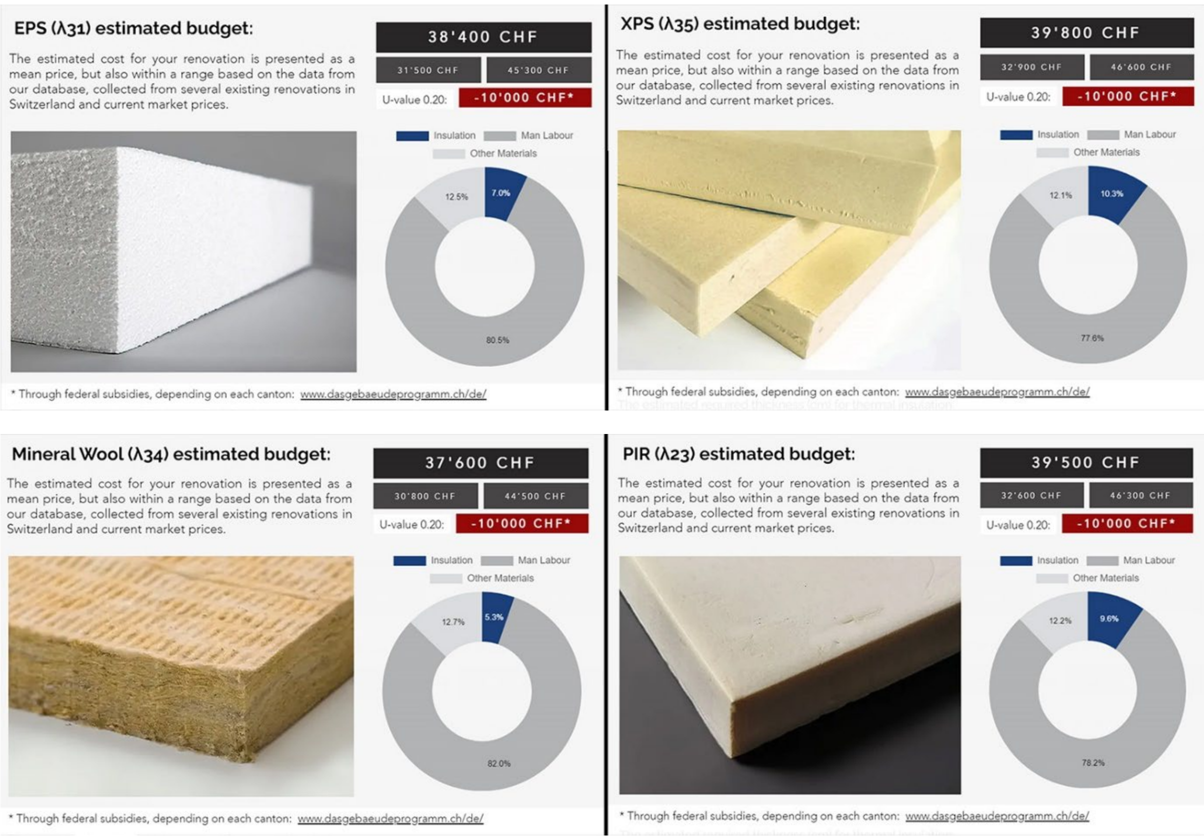

Figure 76. Results for traditional insulation from the online tool.

The previous figures show that the average price of the high-performance aerogel render is very close to traditional products in the calculated scenario, considering the average values. However, depending on the complexity of the building and the costs of the company which applies the material, it lay within the same price range. In fact, the sensitivity of the results is presented below for U-values of 0.25 and 0.20 (glazing 30% scenario).

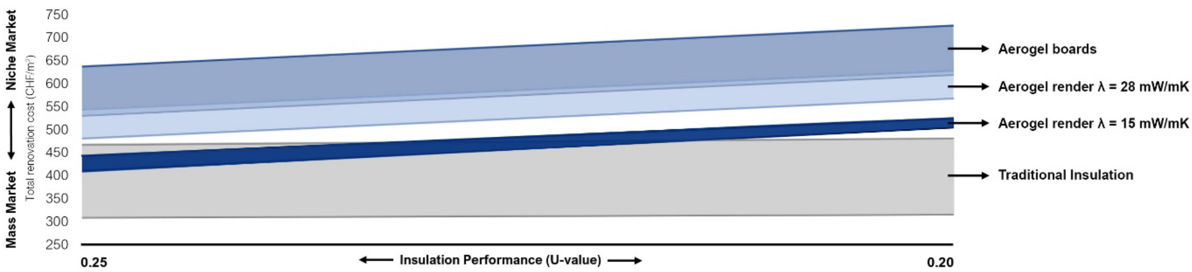

Figure 77. Sensitivity of the results from the online tool.

In summary, an ultra high-performance aerogel render has the potential to leave the niche market of current aerogel products, fostering the use of aerogel more widespread in Switzerland and Europe.

Besides the total cost estimation for renovation presented in this project, the analysis showed the difference in man labour depending on the performance of the product. In particular, the cost of man labour for using high performance aerogel products are lower compared to traditional insulation due to the lower work on details and window reveals. Moreover, the man labour costs of insulating renders can be lower compared to insulating boards, nevertheless the cost is quite linked to the applied thickness. However, despite that current market's best performing aerogel renders (λ = 28 mW/mK) are similar to insulating boards, it is not the case for renders of lower performance, such based on other types of insulating aggregates (perlite, eps and so forth), as the required thickness would require higher costs on man labour:

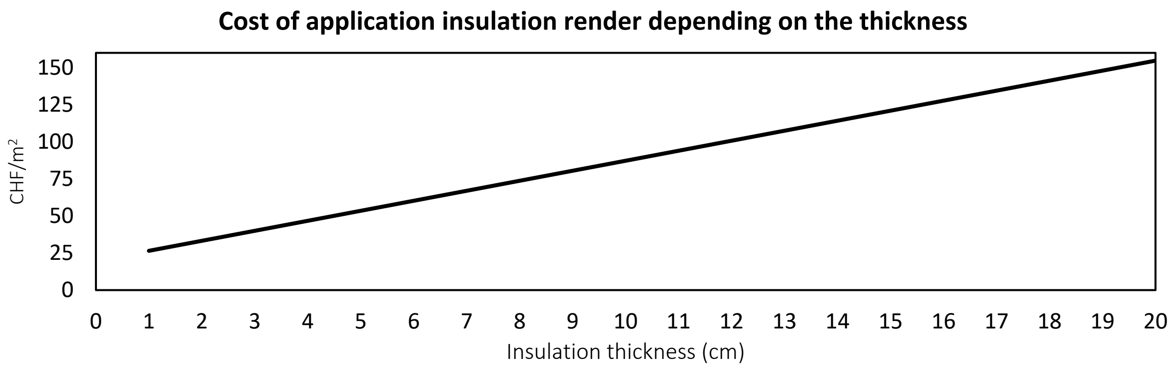

Figure 78. Application costs if insulating renders according to their thickness.

The previous graph shows that low performing insulating renders would require higher man labour costs compared to insulating boards. In contrast, aerogel renders with a similar performance to aerogel boards decrease the cost of man labour becoming overall more attractive, presenting a higher potential for its application on bigger volumes overall, with total costs much closer to traditional insulation products.

4 Conclusions

A step forward towards the development and market launch of ETICS based on aerogel insulation renders with mineral binders with low mechanical properties can be obtained. Especially, for the critical step of upscaling from the lab scale to the application as a façade system. This project has provided an improved ETICS which can improve the robustness during the application compared to conventional insulation render systems. Moreover, for the cost of high-performance aerogel façade systems, including the achievement of higher insulation standards (for obtaining subsidies), this project has provided a better understanding of the renovation costs for Switzerland, thus presenting a more realistic approach. A free online platform to get a cost estimation and potential savings has been developed, in order to show how aerogel insulation can become more competitive, thus more feasible economically.

From the technical point of view, this project brings technological innovation to enhance, during the application, the robustness of aerogel insulation renders with low mechanical properties based on mineral binders. In this sense, the project demonstrated the innovation through the application of an enhanced ETICS system based on a new high-performance aerogel render through the renovation of 40m^2 façade of a villa in Lenzerheide.

In particular, two main innovative aspects have been studied and achieved. On the one hand, it has been found that the application of a deep primer on the substrate promotes a better curing of the mineral binder through, thus improving overall mechanical properties. In fact, it has been shown that substrates can have a high impact on the stability of the render due to water sequestration once the render is applied. This effect can be controlled, as shown in this project, by the application of silane/siloxane hydrophobizing agents to the substrate. The surface treatment enhances the degree of hydration of the mineral matrix, thus improving the mechanical properties up to some extent.

Moreover, it has been proven that the solution can be effectively applied to a wide range of substrates, from concrete, clay brick, calcium silicate block and nature stones, achieving in all cases, a partial hydrophobization of the surface. In fact, the solution is suitable for the typical on-site conditions for other materials based in mineral binders in terms of temperature and humidity: application between 5 to 35 degrees and avoid direct rain on the applied material until the ETICS is finished.

Even more, at a system level, this project provided a new configuration of ETICS for high performance aerogel renders, in addition to the treatment of the surface, by the inclusion of mechanical fixations to the protective adhesive mortar/embedded mesh, enhancing further the robustness and long-term durability of the constructive system.

The durability was assessed by a modular construction with testing plates with the same façade setup has been built to perform the study based in systematic mechanical and physical tests during one year for two types of mineral aerogel renders, allowing the comparison of different aspects of the material properties. The results showed that the new proposed façade system provides significant improvement in mechanical stability and long-term durability.

From the commercial and economical feasibility point of view, this project provided a better understanding of the renovation costs of traditional and aerogel solutions, based on the analysis of every aspect of the renovation, thus presenting a more realistic cost calculation. In particular, it has been found that using high-performance aerogel insulation (λ>20mW/m·K), and even more aerogel renders, the man-labour costs can be reduced (particularly expensive in Switzerland). Indeed, the results of the analysis showed that considering all the costs of a renovation, including aspects typically not taken into account in renovation budgets, such as façade details rework, window reveals and connections and terminations, the costs of using traditional insulation is often much higher than expected. In fact, the higher performance of aerogel products and even more high-performance aerogel renders promotes and important reduction on such costs, ending up in much more competitive final overall renovation costs.

In fact, the achievement of higher insulation standards can be obtained without deep façade renovations using aerogel, providing the benefit of obtaining subsidies from the federal administration. Indeed, through this project, a free online tool to get a cost estimation and potential savings has been developed, which provides realistic calculations for renovation using traditional and aerogel insulation, showing that aerogel insulation is more competitive than expected. The tool has the potential to improve the market dynamics of aerogel insulation for a better market penetration of such type of products and is expected to be actively used to promote aerogel insulation. Nevertheless, the biggest potential can be achieved by ultra high-performance aerogel renders in terms of overall cost, thus more feasible economically.

5 Outlook and next steps

The implementation of the findings of this project will be achieved in through the market launch of a high-performance aerogel render by Aeroskin Tech AG in the short term, and the market distribution of the latter aerogel render by Agitec AG. Moreover, the free online platform will be widely used by Agitec AG for the commercialisation or Aeroskin Tech aerogel render, but also for their broad range of aerogel products and façade systems.

Further implementation of the results has already taken place, by the introduction of deep primers in façade systems and its effect on the water absorption capacity of building materials, in particular, the ones used in façades of buildings. The knowledge has already partially been implemented last Fall semester in the Materials 3 course for Civil Engineers, of the Institute for Building Materials at D-BAUG – ETH Zurich. The course “Building Physics” is a practical lab course of 4 hours (during 8 – 10 weeks, with groups of 8 – 10 students each week). The lab course covers the basic principles of buildings physics, and in particular, thermal insulation, water and moisture transport and durability are presented through laboratory tests. The course is being taught by Dr. Daniel Sanz Pont and Heinz Richner every Fall semester. Nevertheless, more concepts will be applied, in particular related to aerogel insulation systems between later this year and next year. This is due to the fact that the Materials 3 course program is “under renovation” and will be provided to the students closer in time to relevant theoretical courses during their 3rd year. However, the new courses are still under planning and designing stage and the knowledge will be presented to the new generation of students to come.

Next steps from a technological point of view should be focused in improving overall ratio between mechanical properties and thermal insulation in order to reduce the thermal conductivity further in aerogel renders. In fact, it has shown that the lower the thermal insulation capacity that an aerogel render can achieve, the better the reduction of total costs can be obtained. Indeed, the potential of an aerogel render with a lambda of 15 mW/mK has presented in the online tool. Here, the application thickness is reduced even further, thus reducing even more the application costs (time to reach the desired U-value).

From commercial point of view, the wide-spread use and validation of the provided online tool should improve the market adoption of aerogel products and in particular high-performance aerogel renders with higher market potential. The online tool will be periodically updated to adapt it to the increase in costs of materials and man labour, in order to keep the calculation as realistic as possible.

6 National and international cooperation

The activities were carried out with partners in Switzerland as follows:

SFOE: Financial support and project coordinator.

Aeroskin Tech AG: Developer of the demonstrated aerogel render (2) and main researcher of the project.

AGITEC AG: Project partner as sponsor and supplier of materials for the façade system (except for the aerogel render 2. Support in carrying out activities in the project such as planning, purchasing, subcontracting, support with in house manufacturing (modular wall), among others.

DE LUCIA AG: Main implementation construction company of the render system and the renovation of the villa. Support also with the construction planning and the modular wall, with the application of the layers (including the aerogel render) to the test samples.

ETH Zurich: ETH Hosts Aeroskin Tech AG as an ETH Spinoff, therefore, it provides access to laboratories and equipment for the required tests proposed in the project.

J. & A. Kuster Steinbrüche AG Bäch: Kuster sponsored the natural stones testes in WP2 (sandstone and limestones).

7 Communication

Not applicable

8 Publications

- Conferences or research papers. None up to date.
- Knowledge partially integrated in the "Building Physics" lab course as described above.
- Free online platform for cost calculation for renovation using aerogel insulation systems.

9 References

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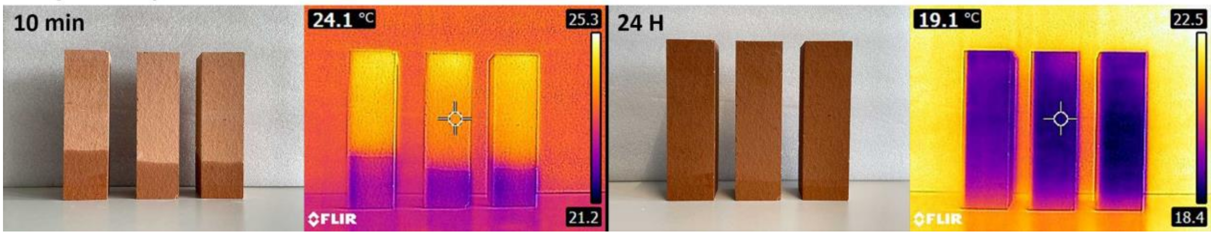
10 Appendix

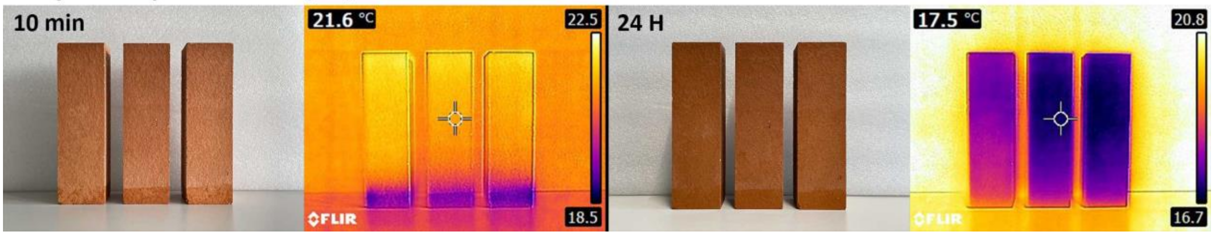
Additional information to the WP2

WP2. Additional information on the deep primers and stones:

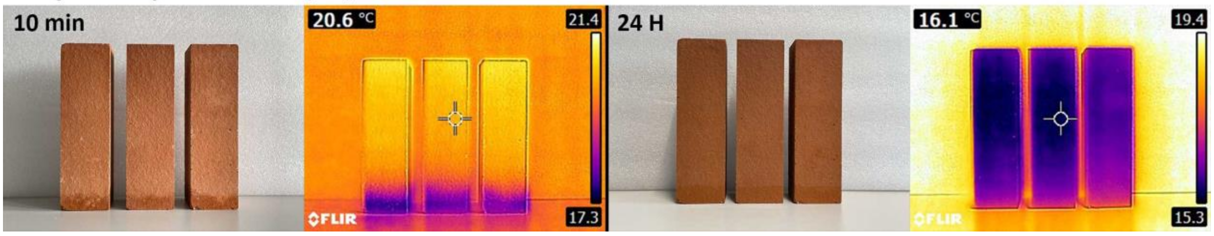
Clay brick | Reference



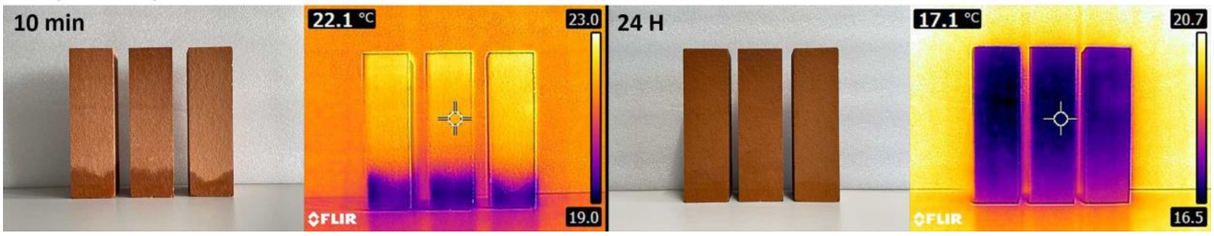
Clay brick | Product 1 (x3)



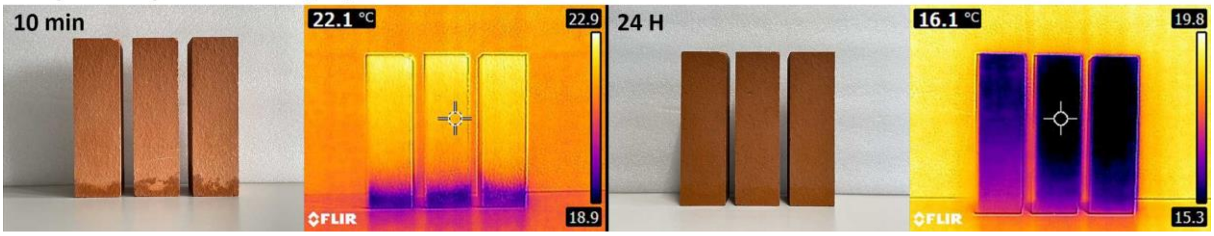
Clay brick | Product 2 (x3)



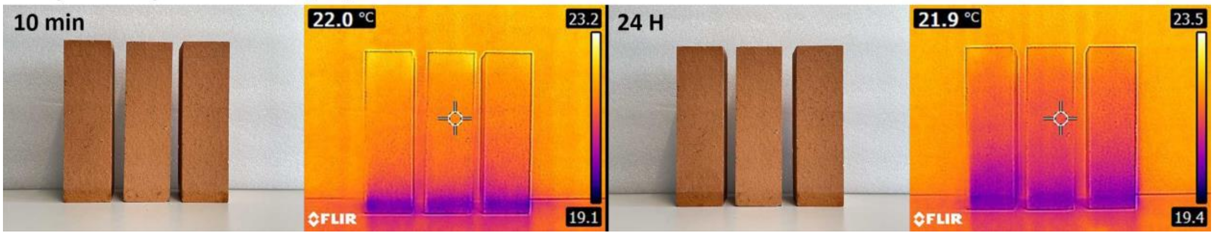
Clay brick | Product 3 (x3)



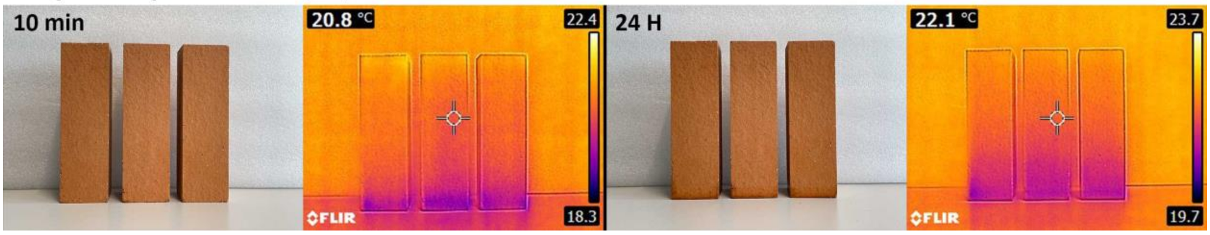
Clay brick | Product 4 (x3)



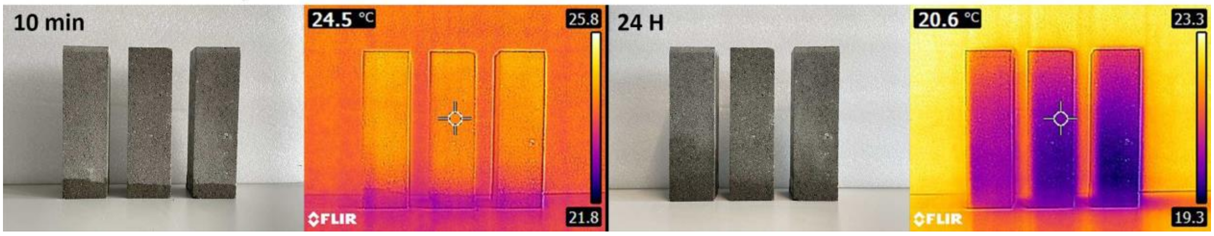
Clay brick | Product 5 (x3)



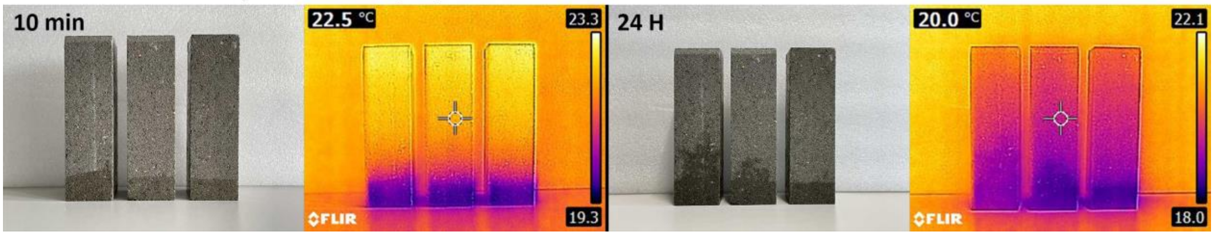
Clay brick | Product 6 (x1)



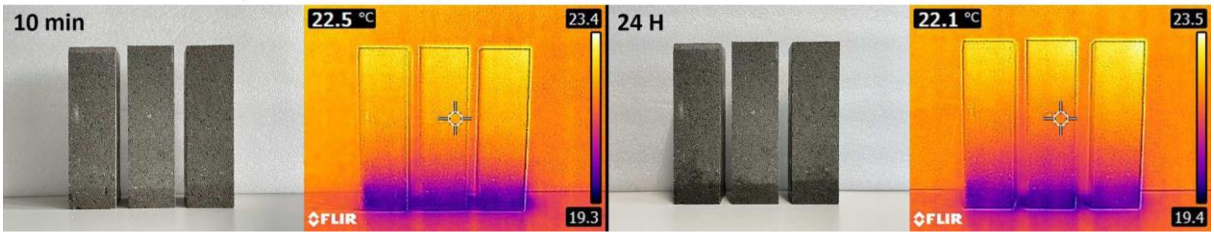
Porous Concrete | Reference



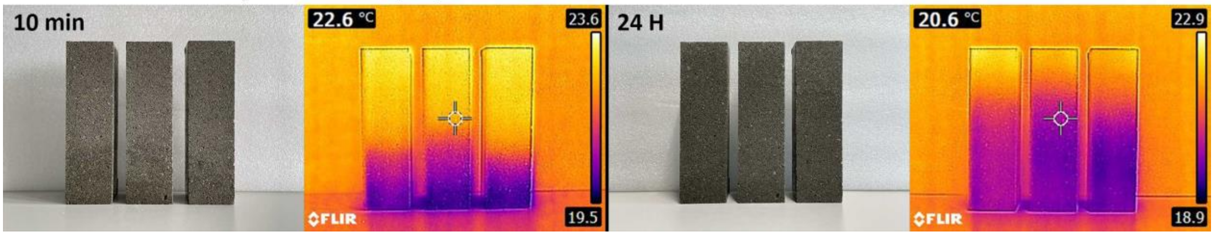
Porous Concrete | Product 1 (x3)



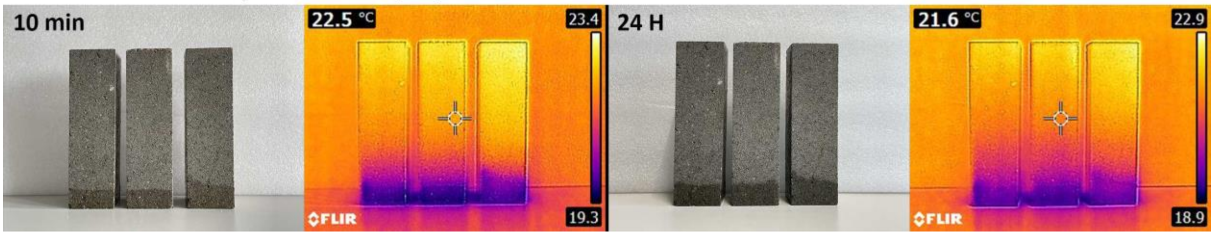
Porous Concrete | Product 2 (x3)



Porous Concrete | Product 3 (x3)



Porous Concrete | Product 4 (x3)



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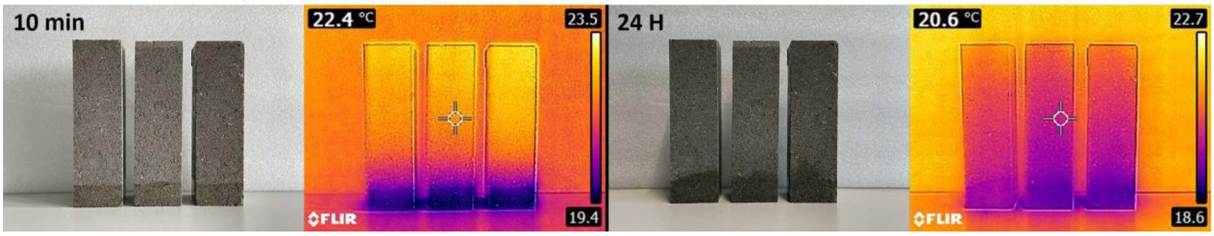
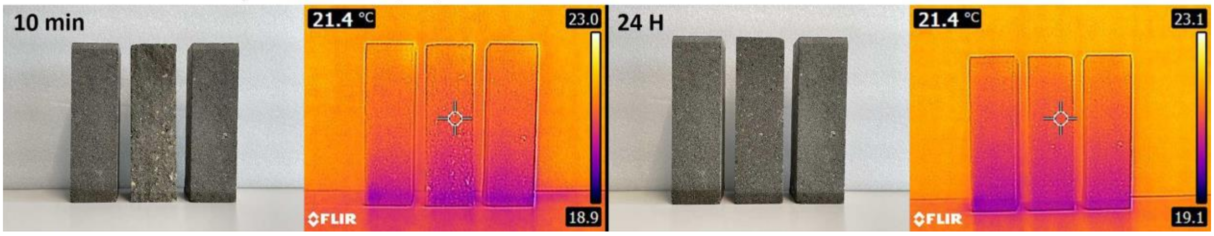
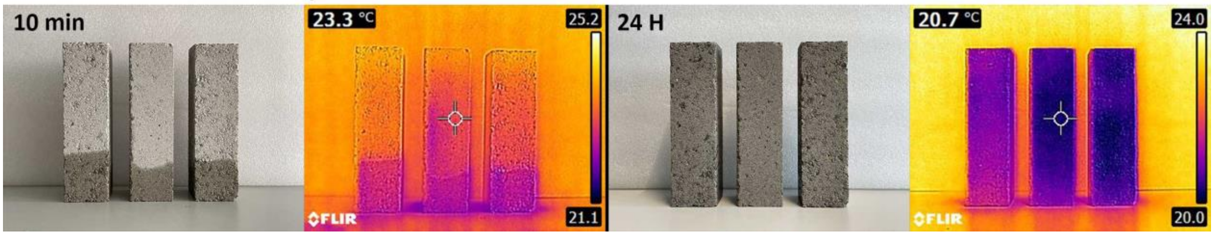


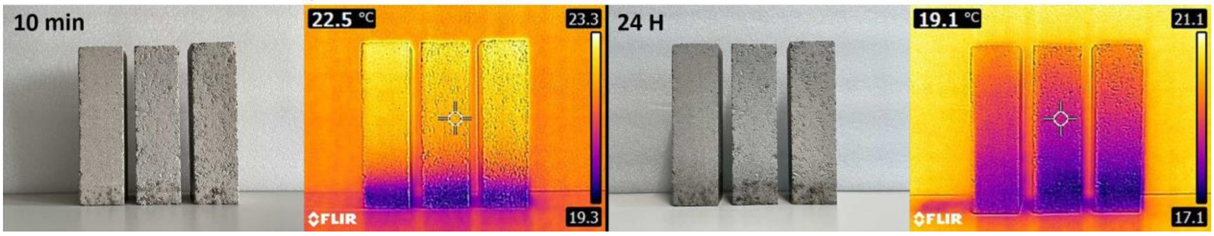
Porous Concrete | Product 6 (x1)



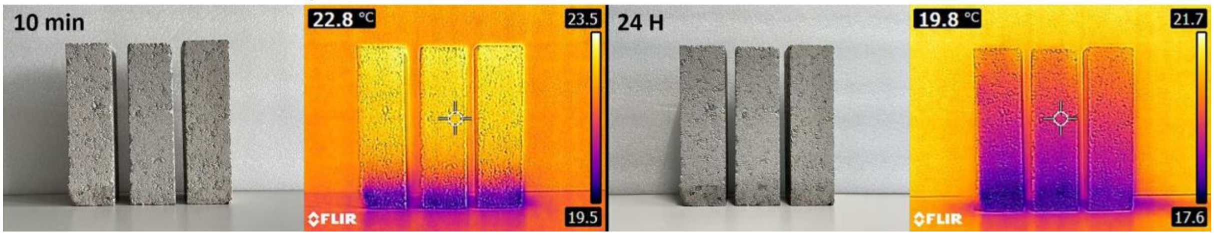
Calcium Silicate Block | Reference



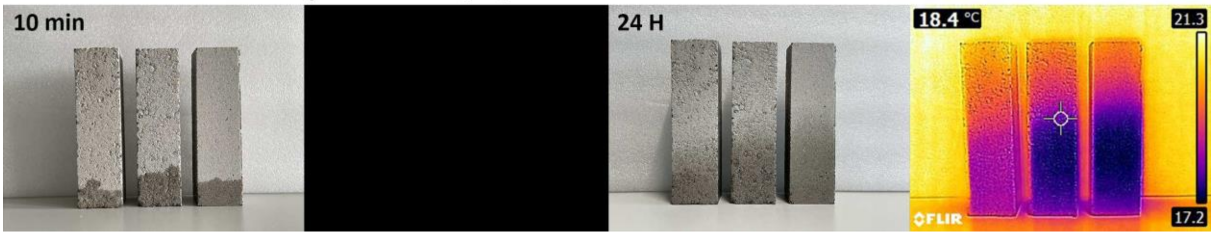
Calcium Silicate Block | Product 1 (x3)



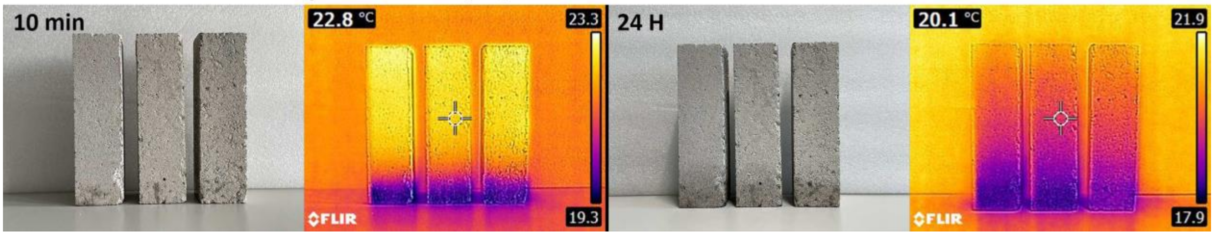
Calcium Silicate Block | Product 2 (x3)



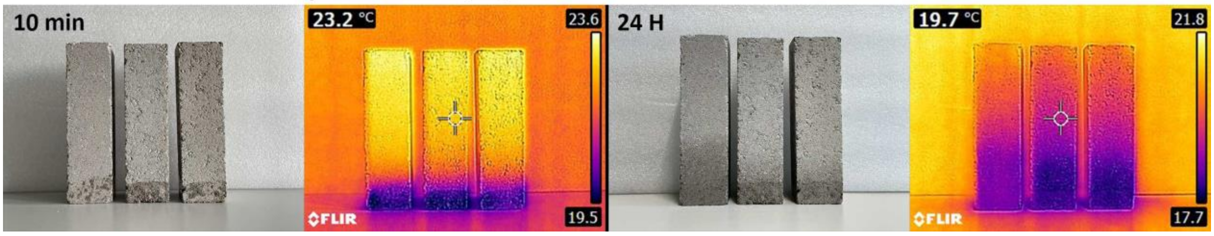
Calcium Silicate Block | Product 3 (x3)



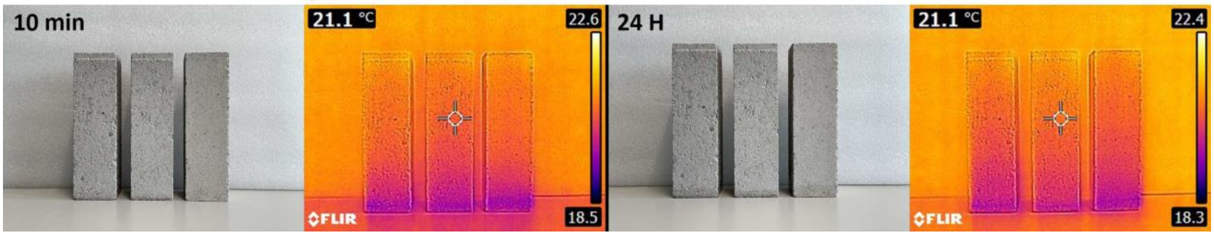
Calcium Silicate Block | Product 4 (x3)



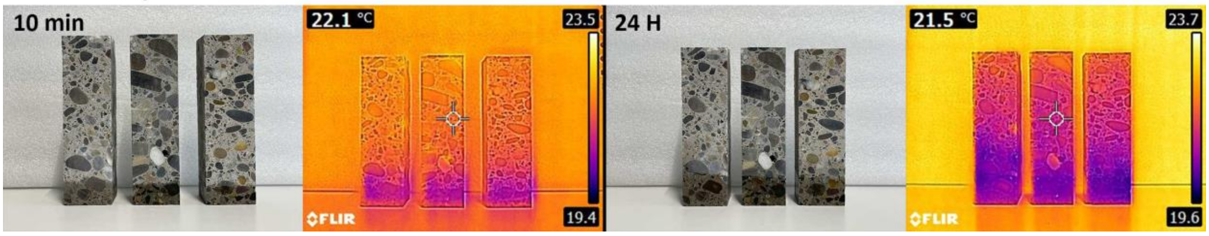
Calcium Silicate Block | Product 5 (x3)



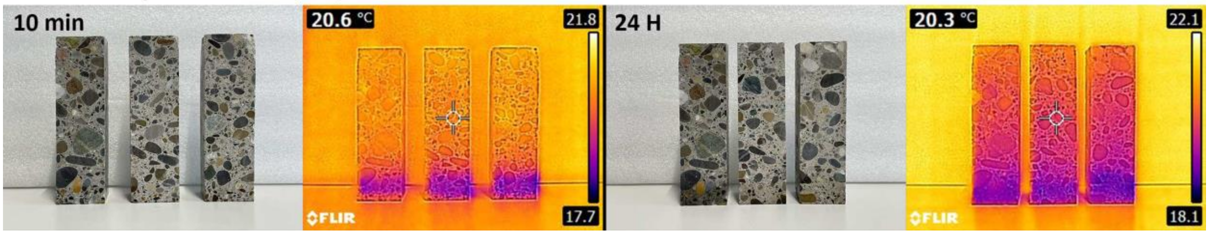
Calcium Silicate Block | Product 6 (x1)



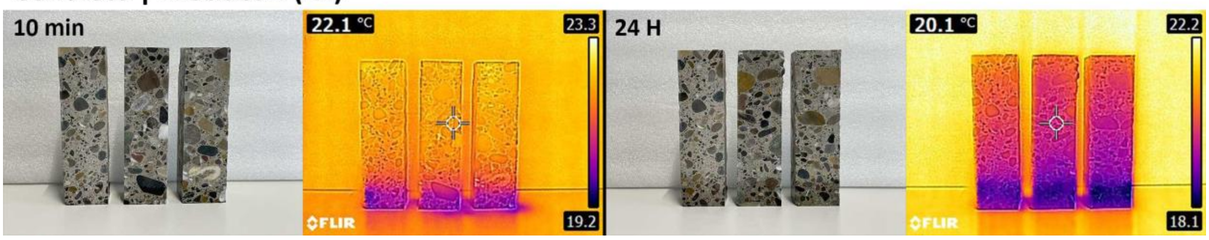
Concrete | Reference



Concrete | Product 1 (x1)



Concrete | Product 2 (x1)



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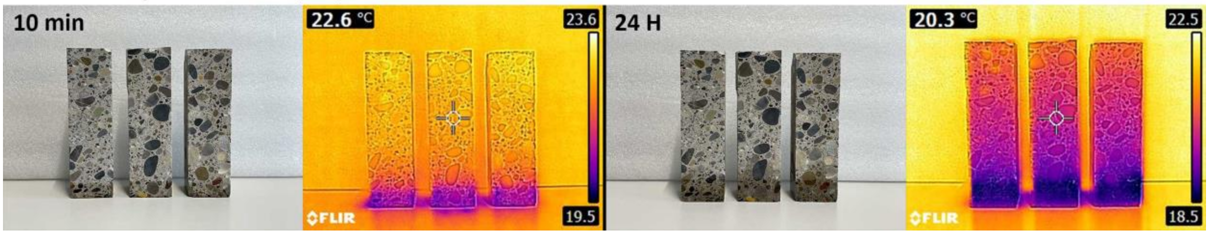

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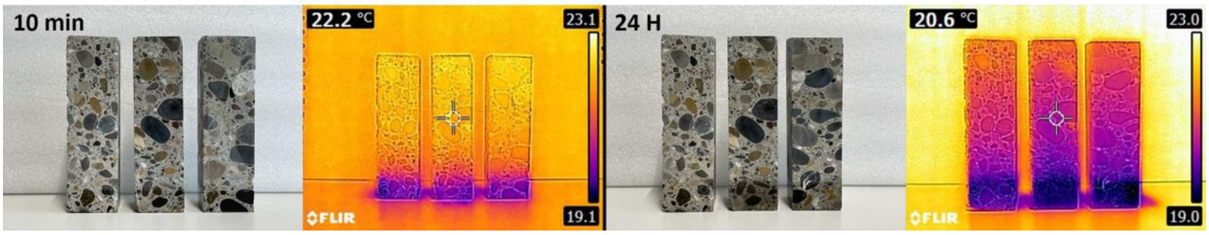

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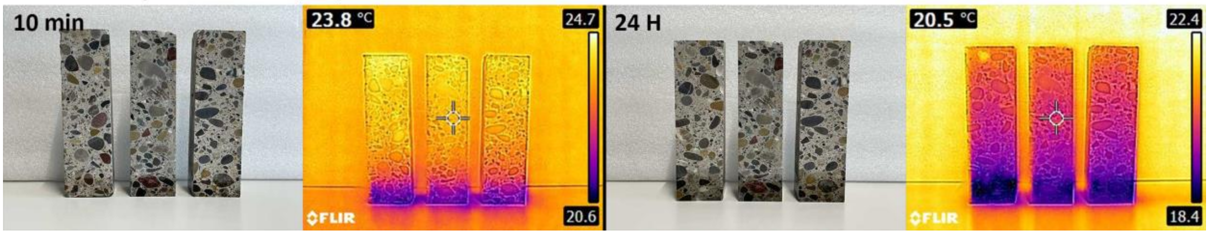
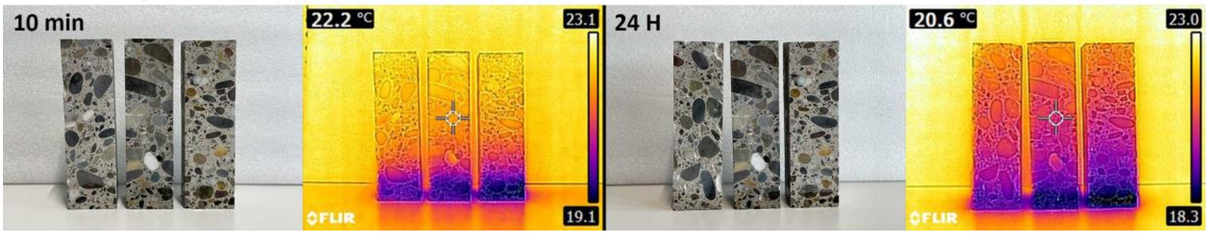
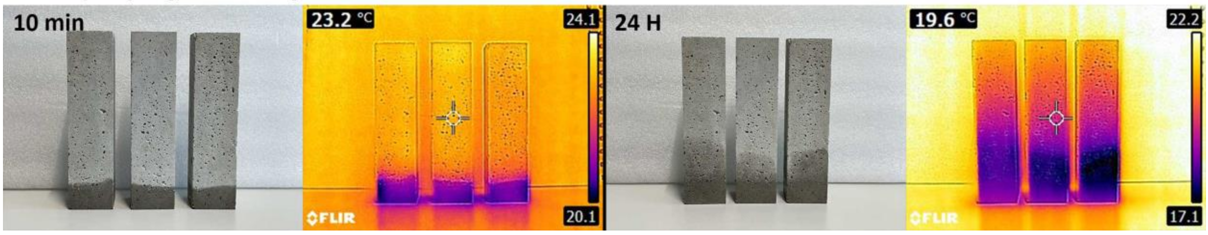


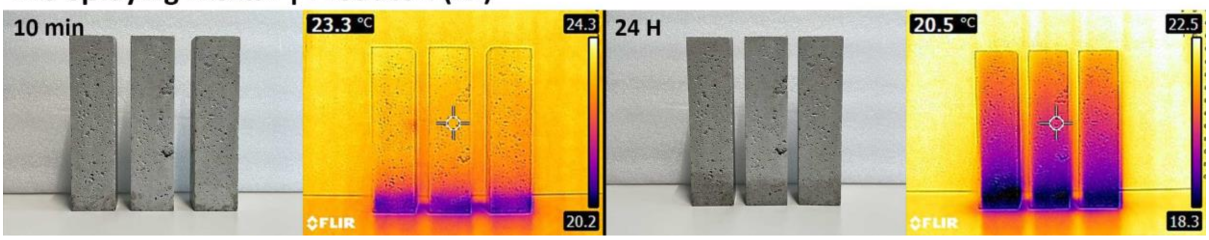
Concrete | Product 6 (x1)



Pre-Spraying Mortar | Reference



Pre-Spraying Mortar | Product 1 (x1)



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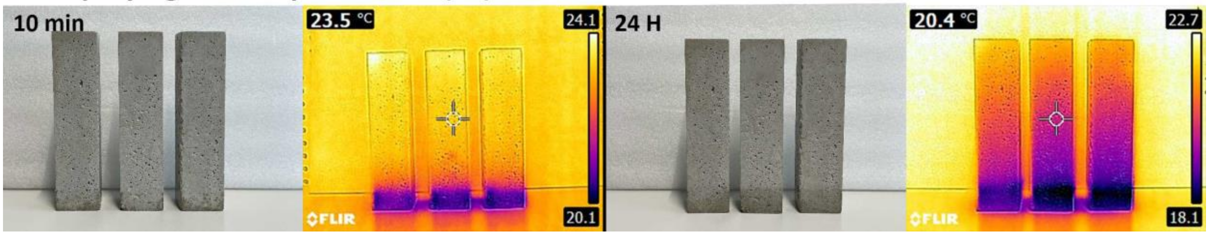
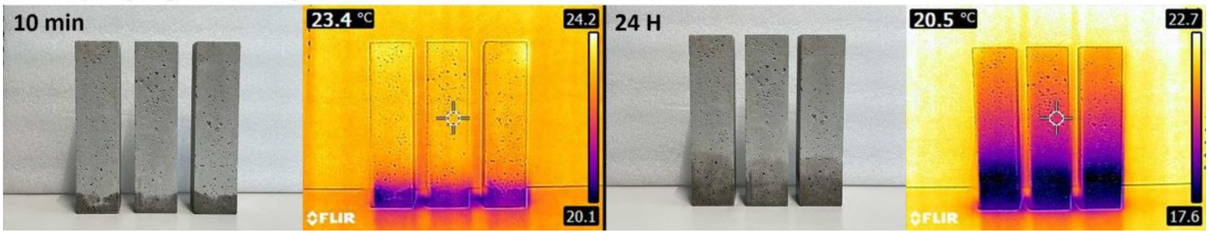
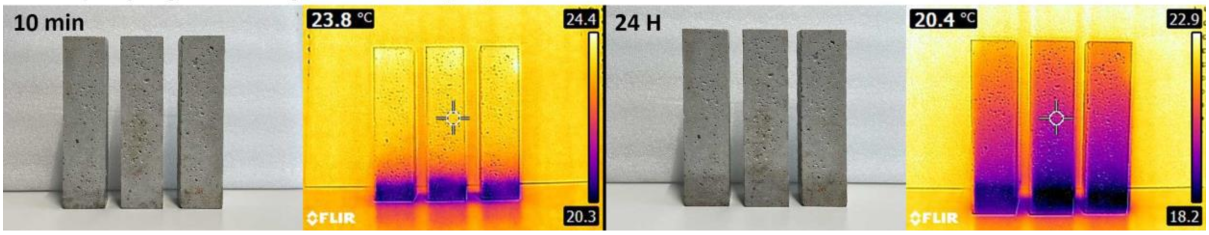


Pre-Spraying Mortar | Product 3 (x1)



Pre-Spraying Mortar | Product 4 (x1)



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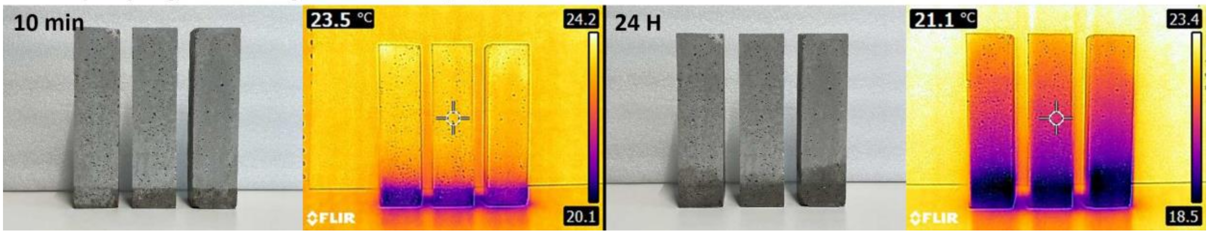

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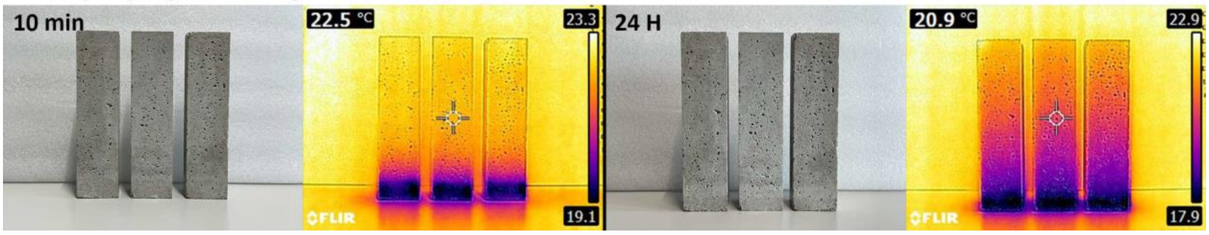
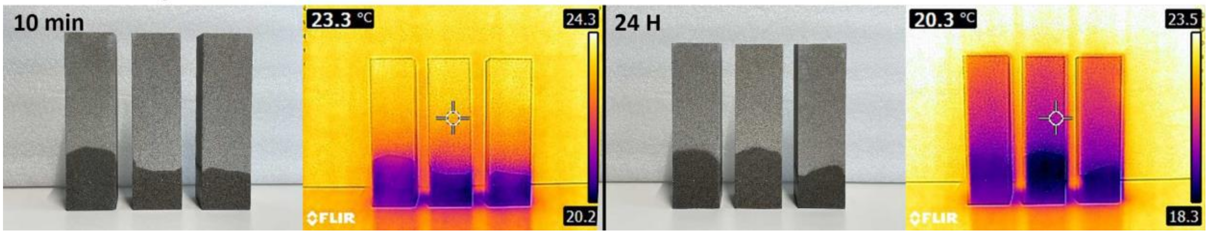
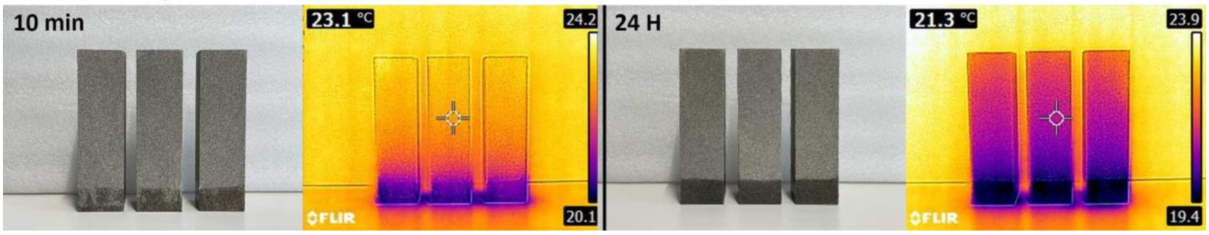


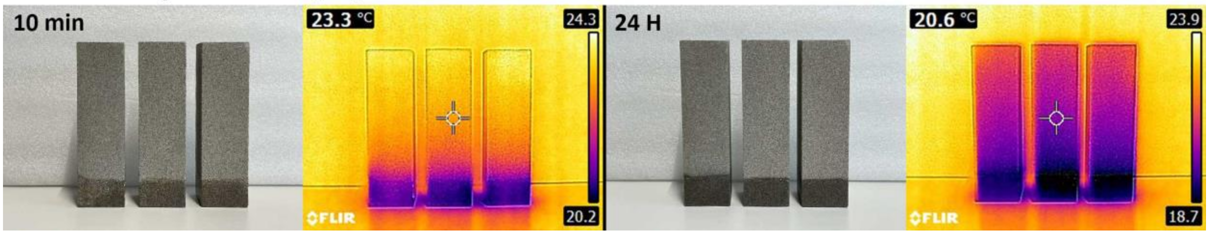
Sandstone | Reference



Sandstone | Product 1 (x1)



Sandstone | Product 2 (x1)



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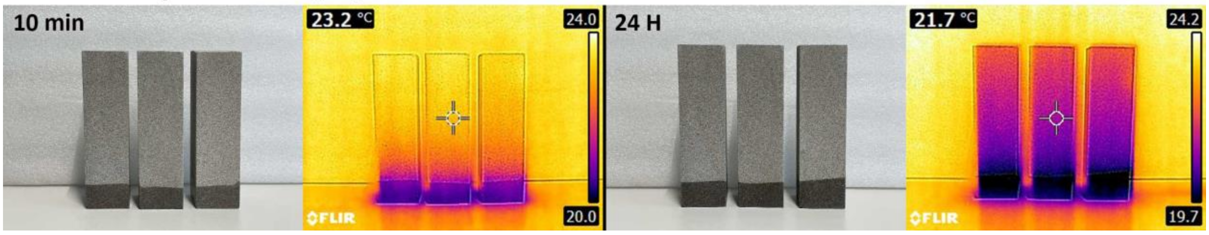

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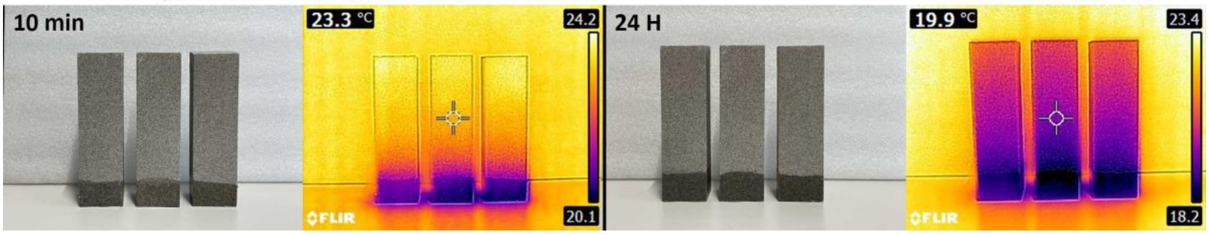

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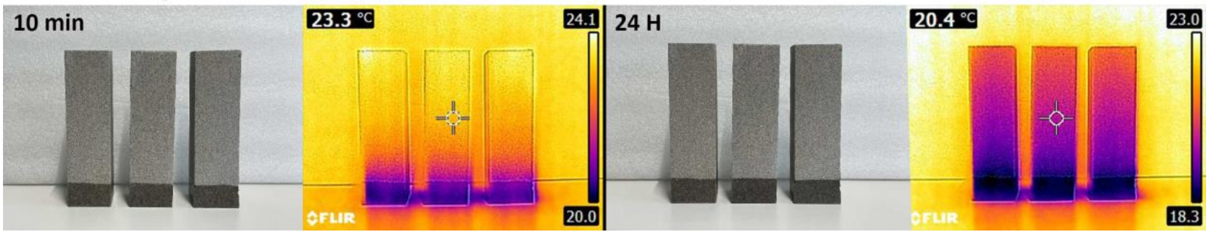
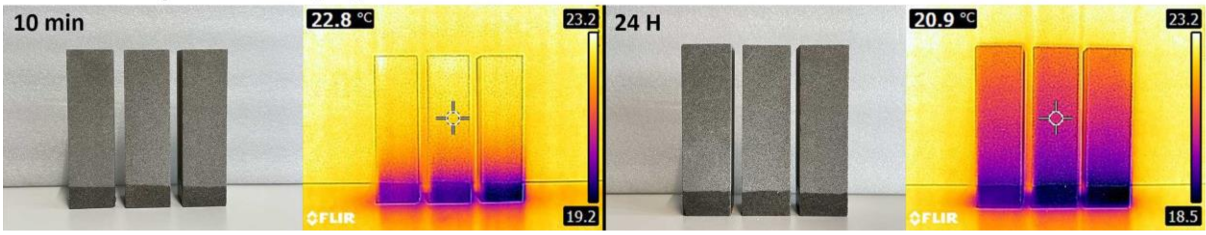
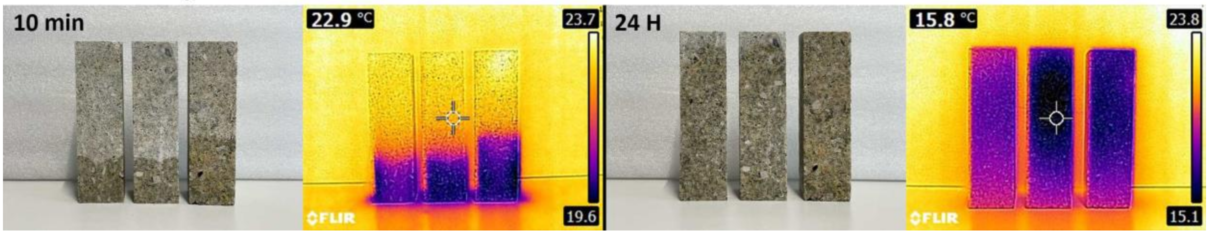


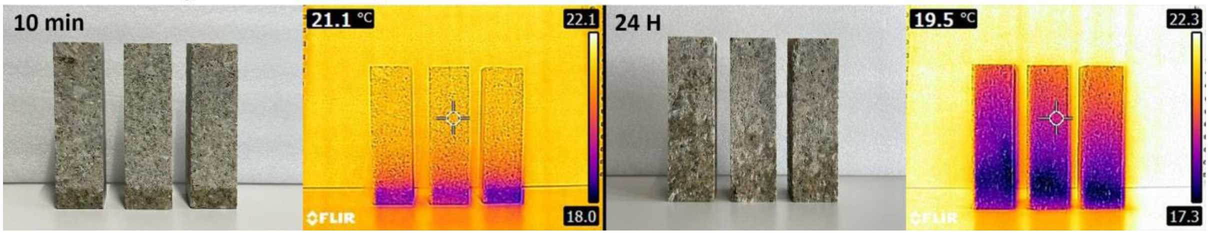
Sandstone | Product 6 (x1)



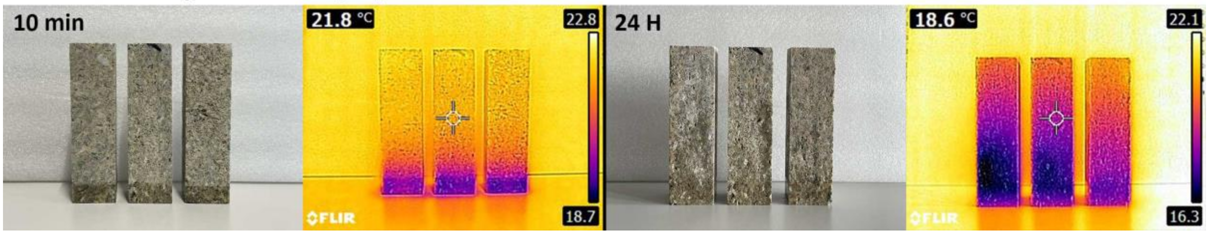
Limestone 1 | Reference



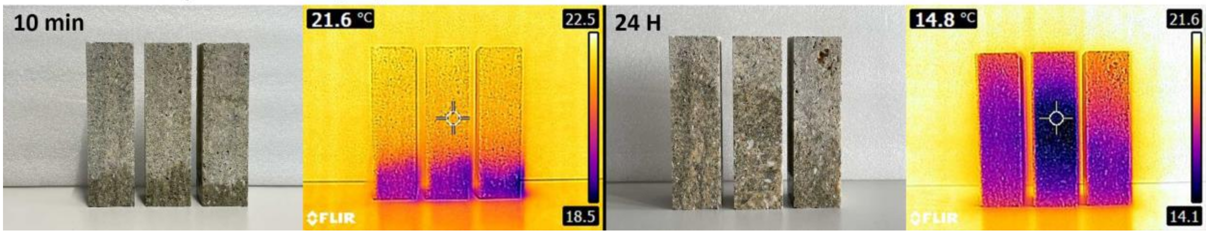
Limestone 1 | Product 1 (x1)



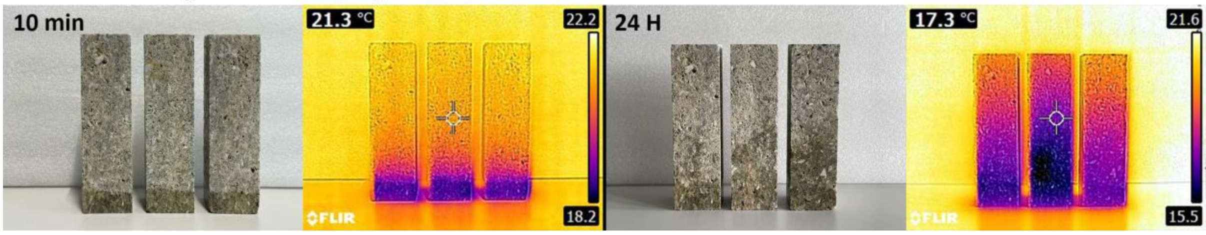
Limestone 1 | Product 2 (x1)



Limestone 1 | Product 3 (x1)



Limestone 1 | Product 4 (x1)



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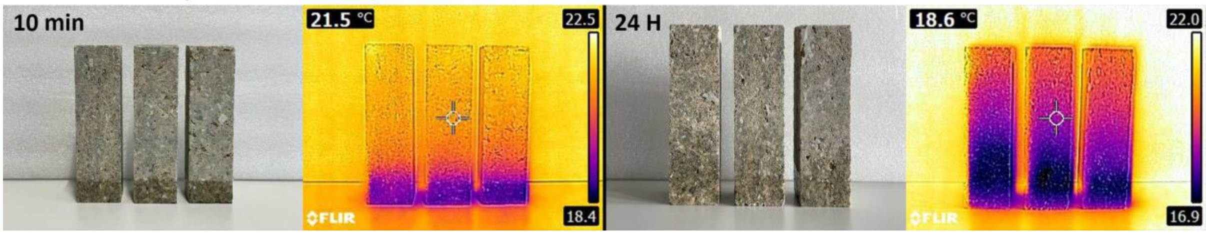
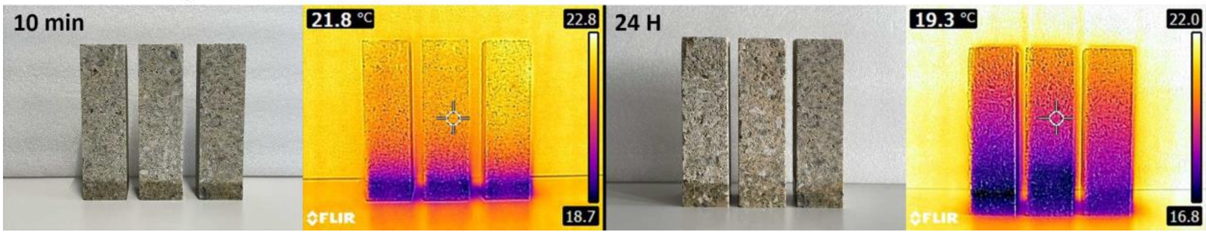
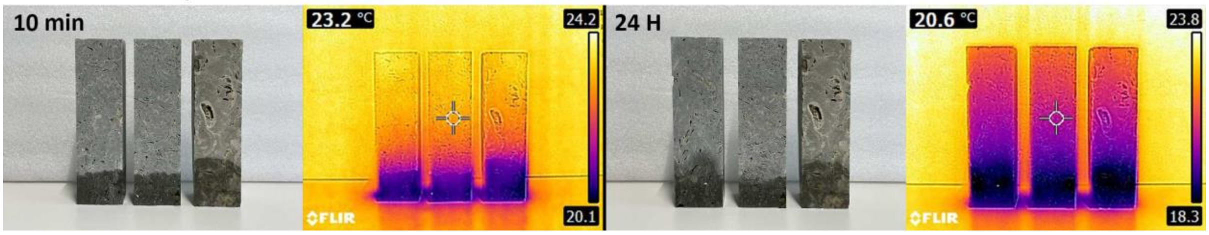


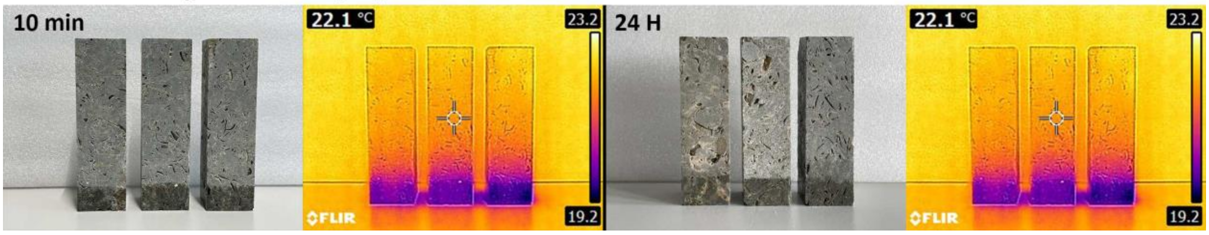
Limestone 1 | Product 6 (x1)



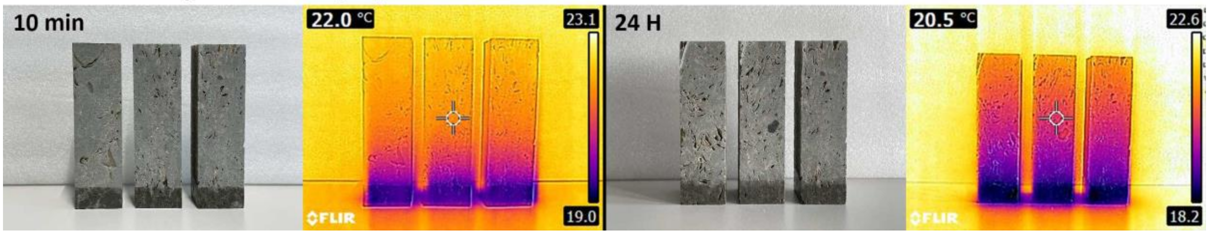
Limestone 2 | Reference



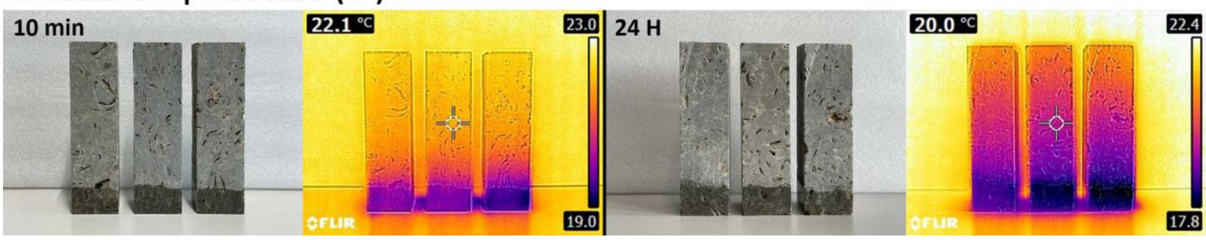
Limestone 2 | Product 1 (x1)



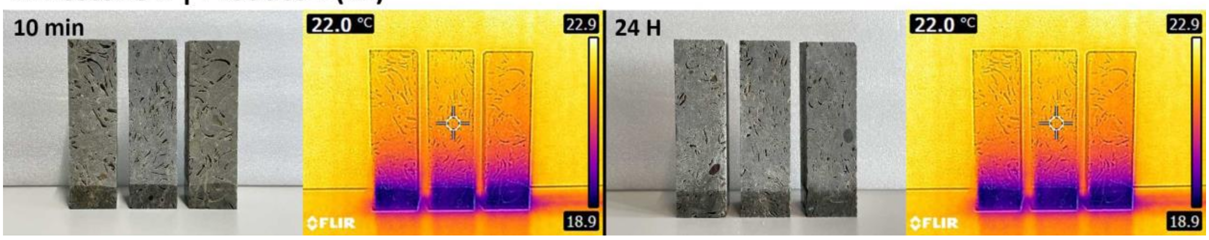
Limestone 2 | Product 2 (x1)



Limestone 2 | Product 3 (x1)



Limestone 2 | Product 4 (x1)



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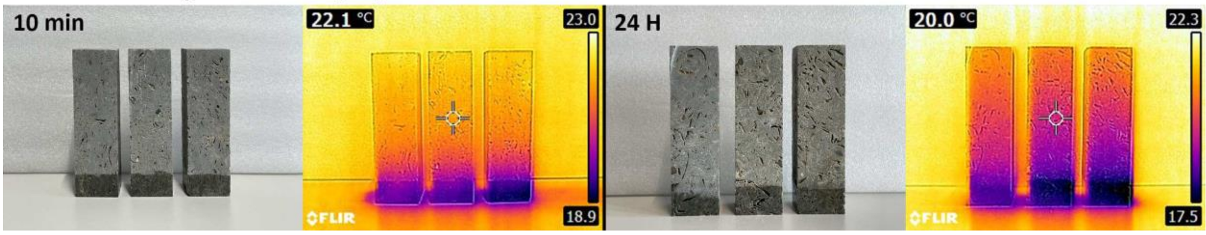

Limestone 2 | Product 6 (x1)