THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Aerogel-based plasters for renovation of buildings in Sweden

Identification of possibilities, information deficiencies and challenges

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Gothenburg, Sweden 2021

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Technical report no 2021:3 Lic /Architecture and Civil Engineering / Chalmers University of Technology

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Cover:

Left: Application of aerogel-based plaster on a demo-wall. Right: Exterior appearance of a building in Zürich, Switzerland, renovated externally by aerogel-based plaster.

Chalmers Reproservice
Gothenburg, Sweden 2021

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Abstract

Aerogel-based plasters are a class of high energy efficient wall finishes with declared thermal conductivities around 30-50 mW/(m·K). Aerogel-based plasters are promising alternatives to substitute conventional insulation materials when renovating uninsulated building envelopes. Aerogel-based plasters have been successfully used in several buildings in a number of European countries but seldom in regions with cold, wet, windy climates combined with freeze-thawing. The potentials for introduction of aerogel-based plasters in Swedish buildings are large as around 27 % of all multi-family residential buildings in Sweden have façades covered by plasters. By using aerogel-based plasters in the renovation of listed buildings, new possible alternatives for solving some of the existing challenges in the renovations of such buildings can be created.

This thesis summarizes the work done on addressing the possibilities and challenges associated with the application of aerogel-based plasters in Sweden. The study is from a risk assessment point of view with focus on the hygrothermal performance, long-term durability and compatibility of aerogel-based plasters with other materials when installed in multilayer wall configurations. Literature review, semi-structured interviews, numerical energy simulations, study visits and laboratory measurements are the selected methods for the purpose of this study.

The results of the study show that APs are promising materials to improve the energy efficiency in buildings when renovating existing buildings in Sweden. However, and despite the large research efforts on aerogel-based plasters, a complete and reliable set of hygrothermal and mechanical properties for aerogel-based plasters is still lacking. Information about these properties is necessary to perform advanced hygrothermal- and risk assessment analyses. To confirm the performance and to justify the higher investment cost of aerogel-based plasters, their long-term durability and compatibility with other building materials need to be further explored as well. For the future introduction of aerogel-based plasters in Sweden, reliable information and documentation are needed. These are needed to evaluate the economic aspects, service life and adaptability of the material to the Swedish building regulations.

Key words:

Aerogel, plaster, render, renovation, energy efficient retrofitting, listed building, hygrothermal, mechanical, compatibility, durability

Aerogelbaserad puts för renovering av byggnader i Sverige

Identifiering av möjligheter, informationsbrist och utmaningar

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Sammanfattning

Aerogelbaserad puts är en mycket välisolerande puts med deklarerad värmeledningsförmåga runt 30–50 mW/(m·K). Aerogelbaserad puts är ett lovande alternativ för att ersätta konventionella isoleringsmaterial vid renovering av oisolerade delar av väggarna. Aerogelbaserad puts har använts framgångsrikt i flera byggnader i ett antal europeiska länder men sällan i regioner med kallt, vått, blåsigt klimat kombinerat med frostcykler. Potentialen för att kunna använda aerogelbaserad puts i svenska byggnader är stor eftersom cirka 27% av alla flerfamiljshus i Sverige har putsade fasader. Genom att använda aerogelbaserad puts vid renovering av byggnader med höga kulturhistoriska värden, kan det skapas nya alternativ för att lösa några av utmaningarna vid renovering av sådana byggnader.

Den här uppsatsen sammanfattar de möjligheter och utmaningar som är förknippade med användning av aerogelbaserad puts i Sverige. Studien är gjord med ett riskbedömningsperspektiv, med fokus på den hygrotermiska prestandan, långtidshållbarhet och kompatibilitet mellan aerogelbaserad puts och andra material i flerskiktiga väggkonfigurationer. Litteraturstudie, semi-strukturerade intervjuer, numeriska energisimuleringar, studiebesök och laboratoriemätningar är de metoder som använts i denna studie.

Resultaten visar att aerogelbaserad puts är ett lovande material för att förbättra energieffektiviteten vid renovering av befintliga byggnader i Sverige. Trots de stora forskningsinsatserna på aerogelbaserad puts, saknas dock fortfarande en komplett och pålitlig uppsättning av hygrotermiska och mekaniska egenskaper för aerogel-baserad puts. Information om dessa egenskaper är nödvändig för att kunna utföra avancerade hygrotermiska beräkningar och riskbedömningar. För att bekräfta prestandan, och för att motivera de högre investeringskostnaderna för aerogelbaserad puts, måste putsens långtidshållbarhet och kompatibilitet med andra byggmaterial undersökas ytterligare. För framtida introduktion av aerogelbaserad puts i Sverige behöver pålitlig information och dokumentation tillgängliggöras. Detta för att ekonomiska aspekter, livslängd och materialets följsamhet mot de svenska byggreglerna ska kunna studeras.

Nyckelord:

Aerogel, puts, renovering, energieffektiviserade renoveringar, byggnader med kulturhistoriskt värde, hygrotermisk, mekanisk, kompatibilitet, hållbarhet

List of Publications

This licentiate thesis is based mainly on the work presented in the following publications:

I. Ali Naman Karim, Pär Johansson, Angela Sasic Kalagasidis, ”Super insulation plasters in renovation of buildings in Sweden: energy efficiency and possibilities with new building materials” proceedings of the *World Sustainable Built Environment Conference (WSBE 2020), Beyond 2020*, Gothenburg, Sweden, November, 2020.

II. Ali Naman Karim, Pär Johansson, Angela Sasic Kalagasidis, “Performance differences and information deficiency about contemporary aerogel-based plasters”, Submitted to the Journal of *Renewable and Sustainable Energy Reviews*, February, 2021.

Additional Publications

Other publications that are related to the content of the thesis are listed below.

III. Ali Naman Karim, Pär Johansson, Angela Sasic Kalagasidis. ”Long-term Performance of Silica Aerogel and Aerogel Based Composites: A Literature Review Highlighting Pathways for Further Studies” proceedings of the *14th International Vacuum Insulation Symposium (IVIS2019)*, Kyoto, Japan, September, 2019.

IV. Ali Naman Karim, Pär Johansson, Angela Sasic Kalagasidis. ”Aerogelbaserad puts-Superisolering för framtiden” *Husbyggaren, nr 6.2020, p. 8-11*, 2020 (In swedish).

V. Ali Naman Karim, Bijan Adl-Zarrabi, Pär Johansson, Angela Sasic Kalagasidis, “Determination of the anisotropic thermal conductivity of an aerogel-based plaster- using transient plane source method”, Submitted to the *8th International Buildings Physics Conference 2021 (IBPC 2021),* Copenhagen, Denmark, August, 2021 (under review: abstract accepted)

Contents

Acknowledgment

Firstly, I would like to especially thank my supervisors, Pär Johansson and Angela Sasic Kalagasidis for their continuing support and feedback. In addition, I would like to thank Paula Wahlgren, both for her efforts as my examinator but also her support with my teaching experiences. I would also like to thank Bijan Adl-Zarrabi and Ingemar Segerholm for their support with the laboratory measurements. In addition, I would like to thank the members of the reference group and the interviewees participating in this study. Thanks, also to Samuel Brunner at Empa for organizing the study visit in Switzerland. Additionally, I would like to thank Heck Wall-system in Germany and ROCKWOOL in Sweden for providing test materials.

The research project has been funded by the Swedish Energy Agency (46822-1). The financial support is gratefully acknowledged.

Finally, I would like to thank my family and friends who are always supporting me.

Ali Naman Karim

Gothenburg, February 2021

Abbreviations

AP	Aerogel-based Plaster
MSI	Moisture Sorption Isotherm
TDS	Technical Data Sheet
TIP	Thermal Insulation Plaster
TPS	Transient Plane Source method

NOMENCULATURE

A_{cap}	Capillary water absorption (kg/(m^2 · min$^{0.5}$))
c_p	Specific heat capacity(J/kg·K)
P	Porosity (%)
T	Temperature (°C, K)
w	Moisture content (kg/m^3)

GREEK SYMBOLS

μ	Water vapor permeability coefficient (-)
λ	Thermal conductivity (W/(m·K))
$\lambda(T)$	Temperature dependent thermal conductivity (W/(m·K))
$\lambda(w)$	Moisture dependent thermal conductivity (W/(m·K))
ρ	Density (kg/m^3)
σ_{ad}	Adhesive strength (N/mm^2)
σ_c	Compressive strength (N/mm^2)
σ_t	Tensile strength (N/mm^2)

1 Introduction

The majority of the existing buildings in Sweden were built during the period 1945–1980 [1] and are currently more than 40 years old. According to the results of the project BETSI [2], an investigation on the technical status of Swedish buildings, around 66 % of all existing buildings had some type of damage and in need of renovation. The corresponding number for multi-family houses built during the period 1961–1975 was around 75% [1]. It is therefore evident that the demand on retrofitting of buildings in Sweden is high.

Aerogel-based plaster (AP) is a class of energy efficient plaster that was first developed around one decade ago [3]. The conventional plaster is often used as a water repellent layer and protects the often uninsulated building envelopes. As the thermal conductivity of AP (30-50 mW/(m·K)) is within the same range of other conventional insulation materials, AP is expected to replace the additional insulation layers when retrofitting uninsulated building envelopes. So far, APs have been successfully used in many buildings in several Central European countries. At the same time, the previous experiences with APs in Scandinavian countries with cold, wet, windy climates combined with cycles of freeze-thawing is limited. The potentials for APs, to be used in the renovation of existing buildings in Sweden is theoretically large. In Sweden, around 27% of all the multi-family buildings are covered by conventional plasters [2]. This corresponds to approximately $(41 \pm 27) \cdot 10^6$ m^2 of plastering façades that can theoretically be fully or partly replaced by new APs. Today, the total energy required for heating of buildings in Sweden accounts for approximately 32% of the total national energy use [4]. By using APs when retrofitting some of these buildings, the energy efficiency in building envelopes can be increased and the energy use in buildings reduced. In addition to the energy saving potentials of APs, the thickness of building envelopes can also be potentially reduced, and a larger inhabitable space will be available.

Renovation and improvement of the energy efficiency of building envelopes in existing buildings is in most of the cases a complicated task [5]. Compatibility of new building materials with existing materials, preservation of character-defining elements of listed buildings, risks for moisture damages and limitation on admissible thickness of building envelopes, set by building regulations are some of the challenges. Regarding the preservation of character-defining elements, in only 41% of the multi-family houses in Sweden, the external walls could be renovated by additional layers of conventional insulation materials [2]. To reduce the thermal transmittance, U-value ($W/(m^2 \cdot K)$), of these external walls to the corresponding U-value in newly built multi-family houses (0.18 $W/(m^2 \cdot K)$ [6]), an addition of around 190 mm of mineral wool would be required. By using APs in the renovation of such buildings, where the number of solutions is limited due to the reasons mentioned above, new alternatives can be introduced for the renovation of buildings with cultural-historical values.

Introduction of a new material such as AP, adapted from other parts of the world, requires special care to avoid expensive failures, especially in climates with high moisture risks such as Sweden. The

Swedish climate is typically recognized as humid, cold and windy combined with cycles of freeze-thawing. A recent failure example was the imported plastering system, the so called EIFS/ETICS [7]. This plastering system was used in large-scale in Swedish buildings without sufficient investigations on its feasibility for the Swedish climate and building techniques. Most of the cases with the ETICS plastering system, resulted in severe moisture damages and large economic expenses. Lack of moisture safe performance when used in Swedish climate conditions, combined with the large access to organic materials in wooden-based constructions, that are frequently used in Swedish buildings, were the main causes of failure. To provide safe and reliable solutions with APs and to justify the higher investment cost of APs, it is of great importance to perform and present accurate risk assessment analyses of APs prior their large-scale implementation in Sweden. To perform such risk assessments for application of APs in Sweden, hygrothermal- (heat and moisture) and mechanical performance of APs, their compatibility with other building materials and long-term durability are such aspects that need to be studied.

1.1 Aim and objectives

This thesis identifies and evaluates the possibilities and challenges for implementation of APs in the Swedish building industry. The analysis is made from a risk-assessment point of view and with respect to the climates and building conditions in Sweden. The focus is on the hygrothermal and mechanical properties, long-term durability and compatibility of APs with other building materials. In addition, the feasibility of APs to reduce the energy use in buildings in Sweden is illustrated.

More specifically, the presented work answers the following research questions:

1. What are the information deficiencies concerning APs, needed for hygrothermal risk assessments?
2. From a practical point of view, what are the major challenges and knowledge gaps that need to be addressed prior the application of APs in Swedish buildings?

1.2 Limitations

In this thesis, the focus is mainly on the hygrothermal and mechanical properties of APs and in respect to the Swedish conditions. Evaluation of other properties of APs are excluded. Regarding the economic aspects of APs, no cost analysis is performed. Likewise, the environmental impacts of APs, in terms of greenhouse gas emissions and embodied energy, are not addressed. In this thesis, only APs that are commercially available are considered. Other laboratory-based trial mixtures of AP developed for research purposes and identified in the conducted literature review are not included. The presented full-scale studies are limited to the ones reported in scientific publications in English, even though there may be other examples of full-scale studies on APs.

1.3 Methodology

To answer the stated research questions in this thesis, several methods has been used. The selected methods include literature reviews, laboratory measurements, numerical energy simulations, interviews and study visits. In this section, these methods are briefly described.

1.3.1 Literature review

To collect information on the research and development of APs, a systematic literature review was conducted (Paper II). The literature review included online references in English, including journal articles, proceedings and conference papers, books and book chapters, standards and websites. The search for relevant scientific references was done via three databases: "Web of Science", "Google

Scholar” and “Scopus”. The query string used for the search in the databases contained *“(*aerogel *AND* plaster**)* *OR* *(*aerogel *AND* render**) OR* *(*aerogel *AND* coating*) OR (*super *AND* insulation *AND* plaster**) OR (*super *AND* insulation *AND* render**)”*. The search was limited to articles that contained the keywords in their title. This limitation was applied to better exclude the irrelevant hits for the purpose of the study. The information on each commercial AP was collected from the website of the manufacturing company and by studying the online version of the corresponding Technical Data Sheet (TDS). The search for TDSs was done via the search engine of “Google”. The final dataset of the work consisted of 38 published documents, 15 websites and 17 standards.

1.3.2 Semi-structured interviews

Semi-structured interviews with Swedish experts and stakeholders in the field of building construction were performed to identify the major concerns related to the introduction of APs in Sweden (Paper I). The interviewees consisted of one building antiquarian, two architects, one senior engineer and one senior expert in plastering systems. The interviewees were selected based on their experience in the field and on recommendation from other experts. All participants are referred to as anonymous in this thesis. The procedure for all interviews was the same. The semi-structured interviews were held separately and at different times and locations. The selected language for the interviews was Swedish. Few days prior to each interview, preliminary questions were sent to the interviewee. The interviews were documented in written notes (no recordings). Examples of common questions are listed below:

- What is the general attitude in the building industry regarding the introduction of new materials/technologies such as APs?
- What are the prerequisites, required by the building industry, for new material to be trusted and used?
- What are the most important factors when evaluating a new material?
- What are the advantages/disadvantages of APs?
- How important is the energy performance when considering using AP in a project?

Apart from the interviews, a reference group, including Swedish researchers, stakeholders and experts in the field, was formed. The challenges within the research project were discussed with the references group and inputs were collected and used to further specify the focus of the work within the research project. Parts of the content concerning future research, discussed in Section 5.2.1 and Appendix B, was developed based on the outcome of the discussions with the reference group members.

1.3.3 Numerical energy simulations

To illustrate the feasibility of APs for use in the renovations of Swedish buildings, the energy saving potentials for APs when renovating plastered multi-family houses in Sweden were studied (paper I). The study was performed by means of numerical energy simulations. A numerical model was developed in the programming software MATLAB-Simulink (version R2017b). In this pre-study, an uninsulated plastered multi-family house in Gothenburg was selected as reference building. Twelve cases were defined and compared. In these case studies, the transmission heat losses through the walls of the reference building, before and after the application of AP, were calculated. Based on the analysis, the magnitude of the energy that could be potentially saved in the reference building was calculated. The simulations were run for one year and for the Swedish cites of Gothenburg and Stockholm. The obtained results from the reference building was scaled up to calculate the corresponding value on national level. The upscaling was based on the available information on the total amount of plastering façade surfaces in multi-family houses in Sweden.

1.3.4 Laboratory measurements

As a supplement to the available information on APs, collected through the conducted literature reviews, a set of laboratory measurements were conducted. The laboratory-based measurements studied mainly the hygrothermal properties of a commercially available AP. The focus of the measurements was to obtain the material properties needed for the continuation of the research project, and to evaluate the suitability of the standard test methods, commonly used for conventional plasters, for APs. In this thesis, the identified details and challenges through the conducted laboratory measurements were summarized and highlighted. The thermal properties (thermal conductivity, thermal diffusivity and specific heat capacity) of the AP were measured using the Transient Plane Source (TPS) method (ISO 22007-2 [8]). A set of wet cup method tests (ISO 12572 [9]) were performed to measure the vapor permeability of the AP. The capillary water absorption of the AP was measured by water suction test (EN 1015-18 [10]). Finally, the moisture sorption isotherm of the AP was measured through a gravimetric procedure (Climate chamber method) (ISO 12571 [11]).

1.3.5 Study visit

To learn more about APs on material-level and the practical details concerning the process of applying APs on surfaces, a study visit was conducted in the autumn of 2019 to the manufacturing factory of a commercial AP. In addition, a number of buildings located in Zurich, Switzerland, renovated externally by AP were visited and visually inspected.

1.4 Outline

The thesis consists of five chapters. Apart from the introductory chapter, Chapter 1, a material description of conventional plaster, aerogel, AP and the application process for AP, collected from the study visit, is presented in Chapter 2. In Chapter 3, the feasibility of APs in Swedish buildings, in terms of energy-saving potentials, is illustrated. The main content of the licentiate, in respect to the objectives of the work, is presented in Chapter 4. In Chapter 4, the obtained results regarding the identified knowledge gaps, possibilities and challenges associated with the introduction of APs in Sweden are presented. The results presented in Chapter 4, are based on the conducted literature review, interviews and laboratory measurements. Finally, the conclusions, discussions, and recommendation for future research are presented in Chapter 5.

2 Material definitions

In this chapter, a brief material definition of AP, conventional plaster and aerogel granules, the main ingredients in AP, is provided. Furthermore, the practical details concerning the application of AP on surfaces are described.

2.1 Aerogel

Aerogels are classified as nanostructured super insulation materials and include any type of material that is derived from molecular, organic, inorganic or hybrid compounds, also called precursors [12,13]. Aerogels are typically prepared by a multi-step synthesis process at which the 3D network of the material with a high proportion of porosity is preserved. Currently, there are several different types of aerogels available. Some examples are: organic aerogels [14,15], inorganic aerogels [16] (Silica (SiO_2) aerogels), carbon aerogels [17], graphene aerogels [18], semiconductor chalcogenide aerogels [19], natural-based aerogels, cellulose aerogels [20] and SiC-based aerogels [21,22]. Despite the numerous types of aerogels, the synthesis procedure for almost all types of aerogels follows a common three steps process: gel preparation, aging and drying [23,24]. These three main steps are explained thoroughly in [13,24–27]. During the synthesis process of aerogels, it is possible to assign an additional feature into the gel network by adding additives or dopants. Often, the aerogel surface is modified after drying, through a reaction with gaseous methanol [24,28]. As a result, the produced aerogels are hydrophobic.

Among the different types of aerogels, mesoporous silica (SiO_2) aerogels are the ones that are commercially most widespread and are mainly used in the construction sector [26], see Figure 1. Table 1 shows the relevant material properties for silica aerogels. Depending on the selected techniques in the synthesis process, aerogels obtain varying material properties. However, high level of porosity, extremely low apparent density and high surface area are some of the key properties that characterize aerogels [25,29].

Table 1. A selection of material properties for silica aerogel [26,27,30].

Property	Value
Density (kg/m^3)	3-350 (Most common: 100)
Pore diameter(nm)	1-100 (On average: 20)
Porosity (%)	85-99.9 (Typical: 95)
Thermal conductivity (W/(m·K))	0.010-0.020
Surface area (m^2/g)	600-1000
Thermal tolerance temperature (°C)	500 (Melting point: 1200)
Tensile strength (kPa)	16
Modulus of elasticity (MPa)	0.002-0.100 (Typical value: 0.03)
Embodied energy (MJ/kg)	53

Figure 1. Photo showing silica aerogel granules.

Aerogels, due to low mechanical strength, are very fragile materials [12]. Consequently, they are often utilized as a compound in composites. The primary advantages of aerogel-based materials are higher energy efficiency and space saving possibilities. Aerogels have received a large amount of attention from the scientific and industrial community during history, and the interest in aerogels seems not to depress either [13]. More research efforts are nowadays focusing on the manufacturing procedure of aerogels to reduce the cost, which is one of the major obstacles for large-scale utilization of aerogels [26]. Apart from the higher processing cost, a complex drying process, diminished mechanical capacity and the dust occurring during the fabrication of aerogels [26], can also be considered as drawbacks for aerogel [13].

2.2 Conventional plaster

Plaster or render is a building material that is normally used as a protective coating on building façades, often uninsulated ones. The internal application of the material refers to plaster, while render is when the material is applied externally [31]. The material composition of plaster can be divided into three major parts: binder, aggregates and additives [32]. The plaster powder is mixed in water to create the fresh mortar. The fresh mortar is then applied on surfaces and façades, manually by hand or by spraying machines. Once the material is dried out, the final hardened product is created. Depending on the choice of binder, aggregates and additives, the material properties of the final product can be modified. Therefore, there are various types of plasters that are used in different contexts and for different purposes.

For binders in plaster, the most common choice is different types of cement, lime, gypsum and sometimes a mixture of cement and lime. Depending on whether the binder in plaster consists mainly of for instance cement or lime, it is normally categorized as cement-based or lime-based plaster. Plaster is also divided into different strength classes based on its mechanical strength that is predominantly dependent on the choice of binder. For aggregates in plaster, natural or crushed sand are the most common options [32]. Depending on the type of plaster, natural sand with round-shaped particles or crushed sand with angular-shaped particles can be incorporated into the mix. An important function of aggregates in plaster is to absorb some of the stresses induced by shrinking in the binder. Aggregates also affects the workability of fresh mortar. In different types of plasters, various kinds of additives can be added to affect the functionalities of plasters. Additives can modify some of the properties, for instance workability, viscosity of fresh mortar, porosity and hydrophobicity of the final product. Water retaining agents, air-entraining agents, and hydrophobic agents are some examples of additives.

2.3 Aerogel-based plaster (AP)

Aerogel-based plasters (APs) or aerogel-based renders are herein referred to as plasters with incorporated aerogel granules [3] and thermal conductivities between 26 and 52 mW/(m·K). In APs, a fraction of the aggregates (sand) is replaced by aerogel granules, resulting in improved thermal performance compared to conventional plasters [3]. The addition of aerogel granules has an impact on other properties of AP than only thermal properties. Lower mechanical strength and higher softness, higher porosity and increased hydrophobicity are example of the properties of APs. Table 2, lists the typical thermal conductivities (λ, W/(m·K)) used to classify plasters. As explained in Section 2.2, plaster refers to the internal application of mortar, while render is when the mortar is applied externally. However, since most APs are for both interior and exterior application, previous publications refer to them as plaster or render regardless of their interior or exterior application. In this thesis, any type of plaster or render with incorporated aerogel granules, and a thermal conductivity of less than 0.1 W/(m·K) is considered AP.

Table 2. Thermal conductivity ranges specified for the classification of building plasters [3,31].

Type of plaster	Thermal conductivity (W/(m·K))
Conventional plaster	$\lambda > 0.2$ (Typical ~0.5)
Conventional thermal insulation plaster (TIP)	(~0.065) $0.1 < \lambda < 0.2$
AP	$\sim 0.026 < \lambda < 0.1$

According to the classifications defined in the standard EN 998-1 [31], plasters with specific thermal insulation properties are classified in the category of thermal insulation mortar (T). This category is divided into two subcategories of T1 and T2 depending on the thermal conductivity of the plaster. APs belong to the category T1. The hygrothermal and mechanical properties specified for plasters in category T1 and T2 are presented in Table 3. In Table 4, a list of the declared material properties for a commercial AP are presented.

Table 3. Selected requirements for hardened thermal insulation mortar (T) specified in EN-998-1 [31].

Material property	Symbol	Category	Requirement
Thermal conductivity (W/(m·K))	λ	T1	≤ 0.1
		T2	≤ 0.2
Compressive strength (N/mm^2)	σ_c	CS I-CS II	0.4 to 5.0
Capillary water absorption (kg/(m^2 · min$^{0.5}$))	A_{cap}	W_c 1	≤ 0.4
Water vapor permeability coefficient (-)	μ–value	-	≤ 15

Table 4. Material properties of a commercial AP declared in the technical data sheet of the product.

Material property	Value
Thermal conductivity (W/(m·K))	0.028
Compressive strength (N/mm^2)	0.45
Capillary water absorption (kg/(m^2 · min$^{0.5}$))	W1
Water vapor permeability coefficient (-)	4-5

For the characterization of plastering materials, the European standard EN 998-1 [31], contains the suggested standards and the corresponding standardized test methods. In Table 5, a list of the recommended standards for characterization of plasters is presented. According to the literature review conducted, the standardized test methods suggested by these standards, have been used for characterization of APs in previous studies. In the reviewed studies, no complications or needs for modifications of the test methods have been reported.

Table 5. A list of the European standards for characterization of plastering mortars.

Standard	Description	Ref.
EN 998-1	Specification for rendering and plastering mortar	[31]
EN 1015-1	Determination of particle size distribution (by sieve analysis)	[33]
EN 1015-2	Bulk sampling of mortars and preparation of test mortars	[34]
EN 1015-3	Determination of consistence of fresh mortar (byflow table)	[35]
EN 1015-4	Determination of consistence of fresh mortar (by plunger penetration)	[36]
EN 1015-6	Determination of bulk density of fresh mortar	[37]
EN 1015-7	Determination of air content of fresh mortar	[38]
EN 1015-9	Determination of workable life and correction time of fresh mortar	[39]
EN 1015-10	Determination of dry bulk density of hardened mortar	[40]
EN 1015-11	Determination of flexural and compressive strength of hardened mortar	[41]
EN 1015-12	Determination of adhesive strength hardened rendering and plastering mortars on substrates	[42]
EN 1015-17	Determination of water-soluble chloride content of fresh mortars	[43]
EN 1015-18	Determination of water absorption coefficient due to capillary action of hardened mortar	[10]
EN 1015-19	Determination of water vapour permeability of hardened rendering and plastering mortars	[44]
EN 1015-21	Determination of the compatibility of one coat rendering mortars with substrates	[45]
EN 1745:2012	Masonry and masonry products- Methods for determining thermal properties	[46]
EN 13501-1	Fire classification of construction products and building elements	[47]

2.3.1 Procedure for application of AP on surfaces

In this section, the practical procedure for the application of AP on surfaces is described. The information is based on the learnings from a study visit to a manufacturing factory of a commercial AP. Therefore, some of the specific details described can be prone to some changes if considering another AP.

The AP is packed in sealed bags of normally 7-10 kg and delivered to the site. The AP is mixed with water at the time of application. Prior to the application of AP, an undercoat layer with a thickness of around 5 mm is smeared onto the surfaces on which the AP will be applied, see Figure 2,a. The main purpose of the undercoat layer is to increase the adhesiveness between the AP and the existing surfaces. The undercoat layer needs to cover at least 50 % of the total surface area and it must be applied one week before the application of AP. Next, the fresh mortar of AP, with the desired thickness, can be applied directly on the surface, see Figure 2,b. It is recommended to use spraying machine for this purpose. The thickness of the AP, applied at a time, is normally limited to 60-80 mm. The application of AP can be done in several steps to maintain higher thicknesses. Once the desired amount of AP is sprayed, the surface layer of AP can be smoothed, seeFigure 2,c,d. The curing time for AP is at least three weeks (around 3mm per day). The required time depends on the conditions on site, for instance climate conditions and the thickness of the AP. To prevent rapid drying and increased risks of cracking, it is important to keep the AP moist and protected from other climate strains such as sun and wind during the curing period (three weeks).

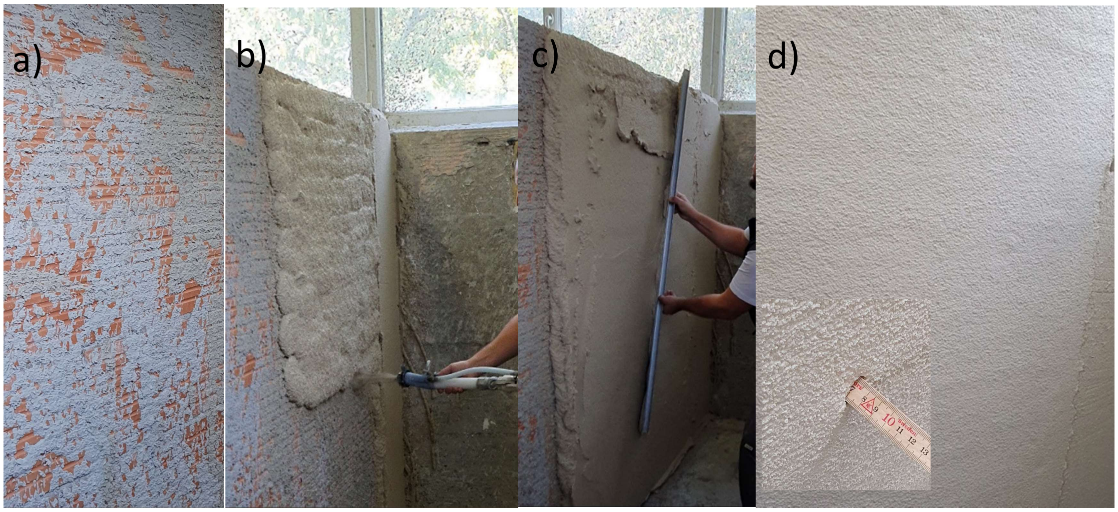

Figure 2. Photos showing the application steps of AP on a demo wall. a) Undercoat layer is smeared onto the surface. b) AP is sprayed on the surface until the desired thickness is achieved. c) The surface of the applied AP is smoothed. d) The final exterior appearance of the AP after the application.

Apart from the undercoat layer, the application of AP includes also other additional plastering layers. Once the AP has hardened, a layer of surface stabilizer is added, prior to the addition of a layer of reinforcement plaster. The reinforcement plaster is added to protect the AP from external mechanical stresses and impact. In some cases, reinforcement meshes are also added to increase the mechanical strength of the plastering system. The exterior surface of the plastering system can be covered by various types of coatings or paints, to obtain the desired external appearance. Figure 3, shows the exterior of a building covered externally by AP. The building was visited by the author in 2019. The visited building in Zurich, Switzerland was covered by AP few years prior to the visit. From the visual inspections, no evidence of major cracks or other damages was identified.

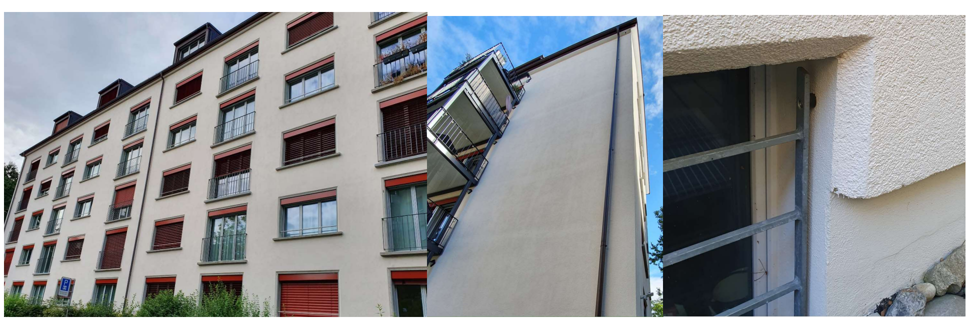

Figure 3. Photos showing different parts of a building in Zurich, Switzerland, covered externally by AP.

3 Feasibility of APs in Sweden: energy saving potentials

In Chapter 1, it was highlighted that there are currently no previous examples on the application of APs in Sweden. As the aim of this work was to identify both the possibilities and challenges related to the future application of APs in Swedish buildings, the feasibility of APs in Sweden was studied. For this purpose, a pre-study with focus on the energy saving potentials, associated with the implementation of APs in renovation of plastered multi-family houses in Sweden was conducted. In this chapter, the details and the results of the conducted pre-study are presented. The study was performed using numerical energy simulations. The content of Chapter 3 is based on the study presented in Paper I [48].

3.1 Reference Building

The selected building for this study was a multi-family house located in Torpa, a residential area on the eastern side of the city Gothenburg, Sweden, see Figure 4. Torpa contains in total 29 three-story, almost identical, multi-family houses with 600 apartments built in 1950. In 15 out of the 29 buildings, the exterior façades are made of aerated concrete and plaster. This residential area is today classified as a significant historical area. However, the buildings in Torpa suffer from a set of problems, such as poor thermal comfort according to the tenants, moisture damage in the building envelope, such as mold growth, and high energy use compared to the required values in building regulations [49]. All 29 buildings in Torpa are in need of renovations. The selected building was one of the 15 buildings with plaster on the façades, as replacing the existing layer of plaster with AP would not significantly alter the exterior appearance of the building.

Figure 4. Left: drawing of the exterior façade of the reference building facing south, and the gable facing west. (Drawing: Arkitektbyrån AB), Right: Photo of one of the plastered buildings in Torpa. (Photo: Annika Danielsson)

The approximate dimensions of different parts of the building were measured from the available drawings and are presented in Table 6. The reference building was ventilated by natural ventilation and district heating was used for the heating system.

Table 6. Dimensions of the reference building based on the available drawings.

Parts	Dimensions	Parts	Dimensions
Total width	60 m	Total height	9 m
Total depth	10 m	Floor area	600 m^2
Window area- south	54 m^2	Window area-north	74 m^2
Window area- east	6 m^2	Window area-west	6 m^2
Wall area- south	486 m^2	Wall area-north	466 m^2
Wall area- east	84 m^2	Wall area-west	84 m^2

Table 7, describes the details of the building components in the reference building. The thickness of the plastering layer in the façades was unknown [49]. Therefore, three thicknesses of 5, 10 and 15 cm were included in the analysis, as the maximum applicable thickness of AP is 15 cm [50]. The ground construction was a concrete slab and for simplicity, it was assumed to have a thickness of 2 m.

Table 7. Material properties and thicknesses of the materials used in different parts of the building envelope in the reference building [50,51].

Material	Component	Thickness (m)	λ (W/(m · K))	ρ (kg/m^3)	c_p (J/kg · K)
Aerated concrete	Wall	0.25	0.14	500	1000
Plaster	Wall	0.05, 0.10, 0.15	0.6	1500	1000
AP	Wall	0.05, 0.10, 0.15	0.028	220	990
Brick	Roof	0.30	0.6	1500	800
Concrete	Ground	2	1.7	2300	900

The renovation strategy in this study was that the existing plastering layer was removed and replaced by a new layer of AP with the same thickness. In Table 8, the thermal transmittance (W/(m^2 · K)) of wall elements in the reference building, before and after the renovation by AP and for different thicknesses of the plastering layer are shown. According to the investigations presented in [2], the average U-value of all plastered, multi-family houses in Sweden was estimated to 0.4 W/(m^2 · K). The calculated U-value for the existing walls of the reference buildings agrees relatively well to the estimated average U-value in [2].

Table 8. Thermal transmittance, U-value (W/(m^2 · K)), of the wall with different thicknesses of plastering layer, before and after the application of AP.

Thickness of plastering layer	0.05 m	0.10 m	0.15 m
Existing wall	0.49	0.47	0.45
Renovated wall by AP	0.27	0.18	0.13
Improvement of U-value	46 %	62 %	71 %

3.2 Model description

As energy simulation was the selected method to calculate the energy saving potentials, a numerical model in Matlab-Simulink (version R2017b) was developed. The simulation model was designed as a 'Lumped model'. This means that the interior volume of the studied building, that was divided in different sections (apartments), was instead modelled as one single zone [51]. The zone had a uniform indoor temperature that varied over time. The lumped model was applicable for the reference building as it was continuously heated and there were no significant indoor air temperature variations [52]. The lumped model is originally utilized for insulated buildings. However, as shown in the study presented in [52], the lumped model can be suitable for uninsulated buildings as well. In Equation (1), the energy balance equation for the building solved in the model is presented.

$$C \cdot \frac{dT_{in}(t)}{dt} = \sum_i Q_i(t) = Q_{heati} \quad (t) + Q_{solar}(t) + Q_{internal}(t) - Q_{trans}(t) - Q_{th.bridge}(t)\text{-}Q_{vent}(t) \quad (1)$$

C	Volumetric heat capacity of the interior building material layers ($J \cdot K^{-1}$)
T_{in}	Indoor air temperature (°C, K)
t	Time (s, h)
$Q_{heating}$	Heat gain from heating system (W)
Q_{solar}	Heat gain from solar radiation (W)
$Q_{internal}$	Heat gain generated by tenants (W)
Q_{trans}	Transmission heat loss through building envelopes (W)
$Q_{th.bridge}$	additional heat loss due to thermal bridges (W)
Q_{vent}	Heat loss by air exchange between interior and exterior via natural ventilation and leakages (W)

All the simulations were run for one year (365 days), with a fixed time step of 1 hour (3600 s). The MATLAB solver 'ode 15s (stiff/NDF)' was chosen with the relative tolerance set to e^{-7}. For internal gains, only heat generated by the tenants was included. It was assumed that there were in total 80 people (20 apartments and 4 people in each) in the building between 17.30 and 07.30 generating 80 W per person. The additional heat losses due to thermal bridges were considered by increasing the transmission losses by 20%. For simplicity, a constant air flow rate of 0.5 1/h was assumed although in reality it can be above this value, especially if one considers infiltration flow rate. This conservative approach helped in not overestimating the results of energy calculations.

The weather data consisted of hourly data of outdoor air temperature, direct and diffuse solar radiation, and angle of incidence. The annual average, maximum and minimum outdoor air temperatures in Gothenburg (Gbg) and Stockholm (Sthlm) are shown in Table 9. For the windows, the transmitted solar radiation was calculated based on the window transmittance for direct and diffuse solar radiation. For diffuse solar radiation, the transmittance was 0.6 while for direct solar radiation, it was calculated based on the angle of incidence. The U-value of the windows and doors were 2.0 W/($m^2 \cdot K$) [53]. No shading system was included in the model. For opaque surfaces, such as façades and roof, a fictitious equivalent temperature was calculated to include the heat absorbed by the surfaces due to solar radiation. A solar absorptivity of 0.6 [51] was assumed for these surfaces.

Table 9. Annual temperature range (°C) of outdoor air in the cities of Gothenburg and Stockholm.

Location	Maximum	Minimum	Average
Gbg	28.4	-14.8	7.6
Sthlm	20.7	-27.8	3.0

3.2.1 Case studies: energy use simulations

In total 12 different cases were simulated, of which 6 cases were simulated for the climate conditions in Gbg and 6 cases for the climate conditions in Sthlm. These cases were represented by a letter each (A-F) and are described in Table 10.

Table 10. Description of the cases used in the energy simulations of the reference building located in Gbg and Sthlm.

Case	Description
A	Existing wall elements covered with 5 cm of conventional plaster
B	Existing wall elements covered with 10 cm of conventional plaster
C	Existing wall elements covered with 15 cm of conventional plaster
D	Renovated wall elements covered with 5 cm of AP
E	Renovated wall elements covered with 10 cm of AP
F	Renovated wall elements covered with 15 cm of AP
Comparison between the cases	
A-D	Comparison between the energy performance in case A and case D
B-E	Comparison between the energy performance in case B and case E
C-F	Comparison between the energy performance in case C and case F

For the energy calculations in multi-family houses in Sweden, an indoor temperature of 21℃ is recommended [54]. However, in most of the apartments in Torpa it was difficult to maintain the originally desired temperatures of 20-21℃ [49]. Therefore, a minimum indoor air temperature of 19 ℃ was set as the requirement in all simulations. As there was no cooling system, no upper limit for the indoor air was specified. Figure 5 depicts the indoor temperatures calculated for each case. The indoor temperature varied freely as it passed the temperature setpoint. As there was no cooling system in the house and the ventilation was constant, the model showed high indoor temperatures. However, they were not relevant because the simulations were focused on the energy needs for heating.

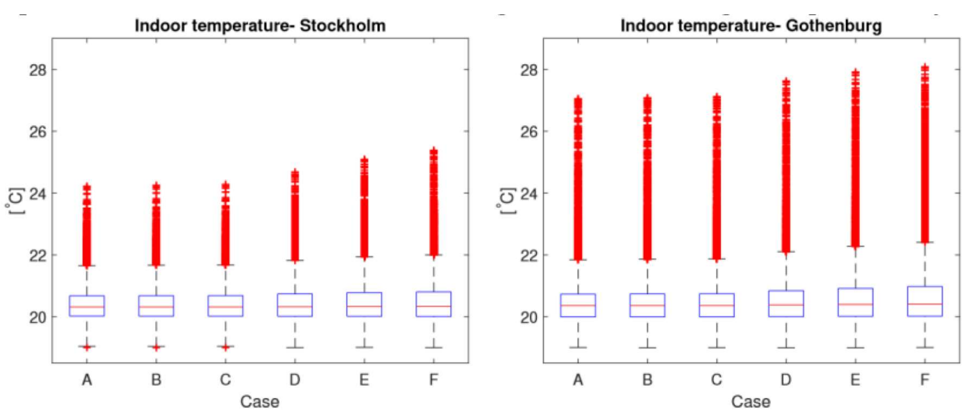

Figure 5. Calculated indoor air temperatures for the simulated cases A-F and for the two cities of Gothenburg and Stockholm. A minimum indoor air temperature of 19 °C was set as the requirement in all simulations.

3.2.2 Results of the simulations

In Table 11 and Figure 6, the results of the simulations performed for the defined case studies are presented. As seen, the total energy use for the reference building in Gothenburg was calculated to around 230-240 kWh/m^2_{floor}. This value can be compared to 203 kWh/m^2_{floor}, the energy use declared in the energy performance certificate from 2011 [49]. The value corresponded to the average energy use for all buildings (29 buildings) in the area and included domestic hot water as well. The estimated values in the simulations seem to overestimate the energy use. However, it was the comparison between the energy use before and after the renovation by AP that was of interest. With that in mind, and considering the number of unknown parameters, the level of accuracy of the model was considered sufficient for the scope of the study which was to compare the different renovation cases.

Table 11. Compiled list of the results for the simulated cases A-F and for the two cities of Gothenburg and Stockholm: Total energy use (kWh/m^2_{floor}) and total transmission loss (kWh/m^2_{wall}).

Case	Gbg (kWh/m^2_{floor})	Sthlm (kWh/m^2_{floor})	Gbg (kWh/m^2_{wall})	Sthlm (kWh/m^2_{wall})
A	242	330	56	75
B	237	323	54	72
C	233	317	52	69
D	187	255	31	41
E	166	226	21	28
F	155	212	16	21

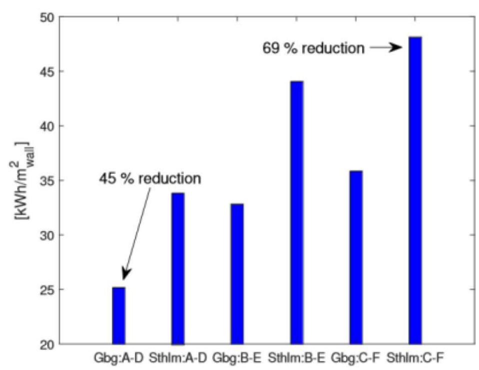

Figure 6. Calculated reduction of transmission losses through the walls of the reference building after the application of AP compared to the heat losses through the existing walls.

3.3 Energy saving potentials in Sweden

In the conducted case studies on the energy performance of the reference building, the lowest and highest amount of energy that could be saved by covering the façades with AP corresponded to 25 and 48 kWh/m^2_{wall} respectively. To consider a rather conservative approach, only 70 % of the lowest amount of energy saving from all the simulated case studies was taken into account. Thus, the minimum energy-saving for renovation of all plastered multi-family houses by AP was considered as 18 kWh/m^2_{wall}.

From the investigations on the technical status of the Swedish buildings presented in [2], the total surface area of the multi-family houses in Sweden covered by plaster was estimated to $(41 \pm 27)\ 10^6\ m^2$. If 10 % of all these houses could be renovated by APs, a total energy of 74±48 GWh could potentially be saved annually in Sweden. This value can be compared to 105 TWh [55], the average total energy use in the building sector in Sweden between 2008 and 2017.

4 Application of APs in Sweden: challenges and knowledge gaps

In this chapter, the main findings regarding the two research questions stated in this thesis are presented. The presented content includes information about the identified challenges, information deficiencies and knowledge gaps concerning APs and their application in Swedish buildings. The findings are presented in three sections based on the outcome of the interviews, literature review and experimental measurements. The main content of Chapter 4 is based on the study presented in Paper II [56].

4.1 Outcome of the interviews

Here, a summary of the collected information through the conducted semi-structured interviews, with stakeholders and experts in the Swedish building industry, is presented. The focus of the interviews was on the possibilities and challenges associated with the introduction of APs in Sweden.

Based on the interviews, a fully clear and standardized procedure for introduction and implementation of new materials/technologies in the Swedish building industry does not exist currently. According to Svensson Tengberg and Hagentoft [57], introduction of new materials is typically done through two alternatives. One is that the material is introduced through a top-down approach, where the decision is taken at a central level in the company and the material is implemented in one or several projects. In a second alternative, the material is introduced directly by the project leader team of a single construction project. According to the interviewees, and as highlighted in [57], the latter alternative is more commonly implemented in practice.

According to the interviewees, the building industry in Sweden takes generally a conservative approach for the introduction of new materials. Two possible reasons were identified. One was the lack of clear structure and documentation for responsibility distribution in case of failure. Each actor strives at redistributing the responsibility to someone else, which results in too much and unclear documentations. Another identified reason was the effect of previous cases of failure. When evaluating a new material for implementation, previous cases of failure with similar, but not necessary the same, materials will be considered in the evaluation of the new material. As explained by the interviewees, the previous cases of failure occurred for different reasons such as insufficient evaluation of the product before large-scale applications. These cases have sometimes ended in severe and large-scale failure. One example mentioned multiple times in the interviews, and described in the introduction of this thesis, was the plastering system, EIFS/ETICS, that resulted in large financial losses in Sweden.

Within the interviews, all interviewees were asked to state their own opinion about the main motivation factors for introduction of a new building material. All interviewees did mention the environmental aspects at some point during the interviews. However, the most mentioned factors were the immediate economic benefits, increased productivity and/or simplification in the application process on site. Along

with the economic benefits, the energy performance of a new material/technique and its impact on the estimated pay-back time was also highlighted. One interviewee mentioned that a new technology can be considered if it can be the solution for a specific practical problem. In such case, the economic benefits can be less prioritized. One example mentioned by the building antiquarian was the possibilities for APs when renovating historical buildings such as Churches in Sweden. Apart from the energy and space-saving benefits, the softer APs can potentially withstand more stresses from the movements in the underlying façade. Therefore, they can be an alternative for the challenges with crack formations on the exterior façades when renovating historical churches.
According to the interviews, the provided information by the supplier of APs, or any other new material, is of great importance. Clear information on necessary and relevant material properties, durability, compatibility of the material with other materials and application instructions were mentioned as important information that are normally requested. Also, adaptability to the building regulations, warranties and whether the producer is responsible only for the material or for its performance as well were emphasized as other important information. It is also desired by the industry that there are previous real-case application projects where the performance of the material has been evaluated.
In general, all the interviewees had a positive opinion about APs, mainly due to its energy and space-saving benefits. What was pointed out as less positive about APs was the potentially higher price of the product, lack of previous experience in Sweden and possible uncertainties regarding the long-term durability of these new materials.

4.2 Literature review: information deficiency

The development of APs was initiated almost one decade ago [3]. Since then, the research on APs has been continued by several research groups. In [56], the development history of APs in different countries was presented. As a result of the research on APs, several laboratory-based trial mixtures, for research purposes, and several commercial APs have been developed. Information on the developed trial-mixtures of APs is available in [56]. Table 12 presents a list of the identified commercial APs and the corresponding material compositions. The presented list is limited to APs with available online TDSs.

Table 12. List of identified commercial AP products.

Product	Country	Internal/External application	Ingredients
Product 1	Switzerland	Both	Hydraulic lime NHL 5, calcium hydroxide, white cement, aerogel granules, light mineral aggregate, water retaining agent, air-entraining agent, hydrophobic agent
Product 2	Switzerland	Both	Hydrated lime, white cement, aerogel granules, light mineral aggregate, organic components, additives to improve the processing properties
Product 3	Switzerland	Both	Hydraulic lime, hydrated white lime, white cement, aerogel granules, light aggregate, water retaining agents, air entraining agents, water repellent agents
Product 4	Germany	External	White cement, hydrated lime, aerogel granules, mineral lightweight aggregates
Product 5	Germany	Internal	White cement (chromate-free), hydrated lime, aerogel granules, mineral lightweight aggregates
Product 6	Germany	Both	Calcium hydroxide, cement, silica granules, perlite
Product 7	Germany	Both	Calcium hydroxide, cement, silica granulate, perlite
Product 8	Germany	Both	Calcium hydroxide, cement, silica granulate, perlite
Product 9	Germany	Both	Calcium hydroxide, cement, silica granulate, perlite
Product 10	Germany	Both	White cement, natural hydraulic lime NHL 5, Poraver (an expanded glass granule produced by the company of Poraver), aerogel, air entraining agent, cellulose ether, dispersion powder based on vinyl acetat and ethylene, starch Ether

In total, 10 AP products were identified in the conducted review. The ranges of the declared material properties for the identified APs are shown in Table 13. Additionally, the commercial APs were evaluated based on the minimum requirements for available technical data for advanced hygrothermal simulations suggested by in [58]. In Table 14 the results of the evaluation are compiled.

Table 13. The range of reported material properties for commercial APs.

Property	Minimum	Maximum	Average	Number of products reporting data on the property
ρ (kg/m^3)	180	290	215	10 out of 10
P (%)	45	90	67.5	2 out of 10
c_p (J/kg · K)	-	-	-	0 out of 10
λ (mW/(m · K))	26	52	35.3	10 out of 10
σ_c (N/mm^2)	0.4	0.8	0.49	8 out of 10
σ_t (N/mm^2)	-	-	-	0 out of 10
σ_{ad} (N/mm^2)	0.08	0.08	0.08	1 out of 10
A_{cap} (kg/(m^2 · s$^{0.5}$))	-	-	W1	8 out of 10
μ-value (-)	4	6	5.05	9 out of 10

Table 14. Evaluation of reported technical data for commercial APs according to the list of minimum required technical data for advanced hygrothermal simulations.

Property	Number of products fully reporting data on the parameter	Number of products partially reporting data on the parameter	Number of products not reporting any data on the parameter
ρ_{dry} (kg/m^3)	4 out of 10	6 out of 10	0 out of 10
$\lambda_{10.dry}$ (mW/(m · K))	2 out of 10	0 out of 10	8 out of 10
c_p (J/kg · K)	0 out of 10	0 out of 10	10 out of 10
μ-value (-)	7 out of 10	2 out of 10	1 out of 10
A_{cap} (kg/(m^2 · s$^{0.5}$))	4 out of 10	2 out of 10	4 out of 10
λ(T)* (mW/(m · K))	0 out of 10	8 out of 10	2 out of 10
$\lambda(w)$**(mW/(m · K))	0 out of 10	0 out of 10	10 out of 10
MSI***	0 out of 10	1 out of 10	9 out of 10

*: Thermal conductivity as a function of temperature (At least 2 values)
**: Thermal conductivity as a function of moisture content (At least 2 values)
***: At least 4 points (adsorption or desorption)

All 10 commercial APs consisted of (white) cement and various lime-based binders mixed with aerogel granules and various types of additives. All but two of the AP products were for both interior and exterior applications. The commercial APs had thermal conductivities between 26 and 52 mW/(m·K) at densities between 180 and 290 kg/m^3.

Based on the information provided in Table 13 and Table 14, there is information available on density and monovalent thermal conductivity of the available APs. At the same time, the lack of sufficient data could be more emphasized for some of the other properties. Data on temperature and moisture dependent thermal conductivities, specific heat capacity and sorption isotherms were most frequently missed. None of the manufacturers provided data on moisture-dependent thermal conductivity or specific heat capacity. Regarding the mechanical properties of commercial APs, 8 of 10 manufacturers provided the compressive strength of the material. In contrast, information on tensile and adhesive strength was not provided. Without knowledge about these properties, the mechanical performance of APs and their mechanical compatibility with other materials cannot be evaluated.

4.2.1 Long-term performance of APs

Building materials installed in the building envelope are normally exposed to various diurnal and seasonal climate-related stresses. Temperature and humidity variations, solar radiation, precipitation and wind are some of the climatic stresses. In the long term, these stresses can lead to deterioration and consequently degradation of the performance of the materials throughout their service life. This phenomenon is often referred to as climate aging of materials [59]. Because the process of real-life aging takes a long time, usually several decades, accelerated aging tests under artificial loading are usually performed to quickly evaluate the long-term performance of materials [60]. In an accelerated aging test, the specimen is exposed to extreme conditions for a short period. Physical and empirical fitting models, such as the Peck model, the Arrhenius equation and the Coffin-Manson relation, can be used to estimate the real exposure service life.

For aging studies on APs, three papers were identified, see Table 15. In [61,62], impact of accelerated aging on the thermal conductivity of a non-commercial AP, a laboratory-based trial mixture was presented. Samples of the studied mixtures were developed by adding various proportions (0-90%) of hydrophobic silica aerogels to commercially available high-performance hydraulic lime-based plaster [62]. Temperature (T), relative humidity (RH), radiation and freeze-thaw cycles were selected as aging factors and applied one at a time. The magnitudes of the loads were estimated to represent the typical climate in Canada. The extent of the tests was chosen to correspond to an estimated service-life of 20 years, using the fitting models mentioned above.

In a recent publication [63], Frick et al. presented the very first results of an ongoing large-scale accelerated aging study on another AP that is not yet fully commercialized. The test setup used in this study consisted of a rectangular chamber and 4 external walls whereof the two longitudinal walls were coated on the inside with a conventional plaster and with the AP, respectively. The layers covered with plaster and AP were exposed to a different number of weather cycles as shown in Table 15. Preliminary results from the evaluation of adhesion, moisture adsorption and visual inspections showed significant moisture uptake and up to 60% reduction in the adhesion of the tested AP.

To sum up, the long-term performance of APs was evaluated in three articles using accelerated aging tests. These studies reported changes in the performance of APs such as increased thermal conductivity, up to 17 %, and decreased adhesive strength up to 60%.

None of the studies involved currently available commercial AP products. Commercial APs contain some additional additives, such as hydrophobic-, air-entraining or water retaining agents, which may be absent in the studied samples. Impact of these additives on the long-term performance of the APs is thus unknown. For these reasons, it is not possible to assess whether the long-term durability results for trial mixtures can be considered fully representative of the commercially available APs.

Table 15. Summary of reported accelerated aging studies on APs.

Aging factor	Test condition	Experimental duration	Est. real lifetime	Result	Ref.
T Freeze- thaw RH	70℃ 40℃, -30 ℃ 90%, 40℃	70 days 170 days/cycles 82 days	20 years	~ up to 17% increment of λ ~ up to 17% increment of λ -	[61]
T Freeze- thaw RH UV radiation, RH, T	70℃, 15 % 40℃, -30 ℃ 70%, 45℃ -, 100%, 55℃	68 days 170 days/cycles 104 days 28 days	20 years	~ up to 4% increment of λ ~ up to 4% increment of λ ~ 16% increment of λ (on average) ~ up to 17% increment of λ	[62]
T, Rain T,T Rain,T,T, Rain	70℃, 1.5 l/m^2.min 50℃, -20 ℃ 1.5 l/m^2.min, -20 ℃, 20 ℃, 1.5 l/m^2.min	20 days/80 cycles 5 days/5 cycles 20 days/30 cycles	-	Observed moisture uptake in the AP 30-60 % reduced adhesive tensile strength Minor chipping of surface Observed crack propagation (crack width<0.15 mm)	[63]

4.2.2 Full-scale performance

Since the early development of APs in 2012, there are several buildings in European countries where APs have been used. Most of these buildings are located in Switzerland, where the first AP product was developed and commercialized. According to [64], about 70 buildings were retrofitted with APs in Switzerland between the years 2012 and 2014. Today, this number has increased to more than 200 buildings [65].

In this section, scientific and published articles reporting full-scale studies on APs are reviewed. A list of these studies and the general details and results are summarized in Table 16 and Table 17.

In the review conducted, 12 full-scale studies on APs were identified. The full-scale studies involved renovations at various scales. In some studies, APs were applied to individual façade elements and in some cases to all façade surfaces. The studies were conducted in Switzerland, France, Austria, Germany, Italy and Norway. All investigated objects were buildings with uninsulated building envelopes. In 11 out of 12 cases, the façade was either brick or concrete. In 7 out of 12 studies, only 5 cm or less of AP was applied. In most studies, 10 out of 12, AP was applied externally. The primary focus of most of these studies was the thermal performance of APs. Eight studies explicitly indicated improved thermal performance with the addition of AP. In the cases studied, the addition of 1.5-6 cm of AP reduced the U-value of the studied walls by 27-70%. A reduction in U-value of more than 50 % was reported in 4 out of 12 studies. Apart from evaluating the thermal performance, it was claimed in 3 out of 12 studies that along with the addition of APs, the risk of moisture damages in the walls was reduced and the thermal comfort in the building was improved. No cases of major damage associated with the application of APs were identified. Minor damage in form of visible cracks was reported once.

The application of APs to surfaces was done manually or with the help of spray machines. However, most studies did not explicitly describe the chosen application method. The application of APs to façades was supplemented by additional layers of plasters to increase the adhesion to the underlying surface and to protect the AP. In addition to complementary layers, reinforcement mesh was also added in some cases. The final exterior surface was covered by various layers of coatings or paints.

The approach and main criteria for selecting the complementary materials for APs were not explicitly described in the studies reviewed. However, there were recommendations from AP manufacturers on what other plasters should be used along with their respective AP and for different types of construction. The information provided on how these recommendations were arrived at was generally not described in detail. It should be emphasized that no study reported any major problems regarding the compatibility of APs with the selected ancillary materials.

Table 16. List of full-scale studies on APs reported in scientific articles.

Location	Aim of the study	Construction before (from exterior)	Construction after (from exterior)	Result	Ref.
Nice-France	Hygrothermal performance evaluation of walls with different thermal insulation configurations.	25 cm Concrete 16 cm Glass wool 1.3 cm Plaster	4 cm AP 25 cm Concrete 16 cm Glass wool 1.3 cm Plaster	The evaluation of the studied wall configurations was carried out through simulations. The results of the experimental study were used to validate the simulation model. The addition of the FR-MINES on the exterior significantly reduced heat losses and moisture risks.	[66]
Nice- France	Thermal performance evaluation of multi-layer exterior walls for different heating operation modes. To determine the optimum wall structure: number and position of insulation layers.	25 cm Concrete 16 cm Glass wool 1.3 cm Plaster	4 cm AP 25 cm Concrete 16 cm Glass wool 1.3 cm Plaster	The results obtained from the experimental measurements were used to validate a developed numerical heat transfer model. The optimal wall structure depended on the selected heating operation mode. In most of the cases studied, AP performed better than other insulation materials.	[67]
Nice- France	Thickness optimization and cost analysis of AP for different climates.	-	4 cm AP 42 cm of brick monomur	The analyses were performed by simulations. The simulation models were validated using the results from the experimental measurements. The optimal thickness of FR-MINES was calculated to be ~ 1.7-4.4 cm and the payback period was calculated to be ~ 1.4-2.7 years, depending on the selected climatic conditions.	[68]
Le Bourget du Lac- France	Hygrothermal performance evaluation of façades clad with AP. Comparison of the theoretical and the in-situ measured U-value.	Brick Plasterboard	AP Brick Plasterboard	Preliminary results from the first six months of measurements were presented. Too much fluctuation in the measured data during the first six months. A longer measurement campaign was planned. More than two times higher in-situ U-value compared to the theoretical value.	[69]
Vienna- Austria	Evaluation of the long-term performance of AP.	20 mm lime-cement rendering 250 mm hollow bricks 15 mm gypsum plaster	4 cm AP with different finishings 20 mm lime-cement rendering 250 mm hollow bricks 15 mm gypsum plaster	Preliminary results from the first six months of an ongoing project (four smaller wall partitions). A longer period, approximately one year, of data collection was required as the quasi-steady state was not achieved.	[70]

				A reduction of the temperature difference between the indoor air and the surfaces was measured up to ~ 4 °C. No visible cracking.	
Vienna- Austria	Evaluation of the long-term performance of AP (3 years).	20 mm lime-cement rendering 250 mm hollow bricks 15 mm gypsum plaster	4 cm AP with different finishings (+ reinforcement mesh in some cases) 20 mm lime-cement rendering 250 mm hollow bricks 15 mm gypsum plaster	A reduction in U-value of up to 64 % was measured. The final finishing coats appeared to have a negligible effect on the hygrothermal conditions in the walls. With fine grained plasters and without reinforcement mesh, small cracks appeared in some cases.	[71]
Sissah- Switzerland	Retrofit of an inhabited 14th century mill by AP. Assessment of energy performance of AP, mold growth risks and thermal comfort in the building. Evaluation of temperature development and water content in the façade over a period of 5 years: hygrothermal simulations.	5-6 cm Portland cement rendering ~45-70 cm limestone quarry	5-6 cm AP + glass fiber reinforcement mesh ~45-70 cm limestone quarry	Reduction of the U-value by ~65 %. Improved thermal comfort. Reduced risk of mold growth. Numerical hygrothermal simulations were performed for five years and for an average cold year in Zurich, Switzerland. For the simulated case with high initial moisture content, the wall was dried out for 1.5 years. In all cases, the quasi steady-state condition was reached after two years.	[72]
Dällikon- Switzerland	Application of six different APs to the south-orientated exterior wall of an office building. Evaluation of the thermal performance and drying behavior of the APs.	Prefabricated concrete	Final coating 2 layers of supporting plaster Reinforcement mesh 2 layers of APs Primer and roughcast Prefabricated concrete	Continuous measurements: energy evaluations were not performed and therefore not reported. After four months of data collection, the layer with Quick-Mix was still damp.	[63]
Berlin- Germany	Retrofit of a 30 m high precast concrete building with AP. Evaluation of the energy performance of AP, using in-situ measurements of the U-value. Evaluation of the temperature development and water content in the façade: hygrothermal simulations.	10 cm steel reinforced concrete slab 6 cm mineral fibre mat 10 cm steel reinforced concrete slab	6 cm AP + a wavy metallic grid 10 cm steel reinforced concrete slab 6 cm mineral fibre mat 10 cm steel reinforced concrete slab	Reduction of the U-value by ~70 %. No visible cracks and hardly visible thermal bridges after two years. For high-rise buildings exposed to driving rain, the best rendering finish must be water repellent and vapor open.	[73]
Turin- Italy	Evaluation of energy performance of AP: heat losses and thermal bridges.	Plaster Brick-air cavity- Brick plaster	Plaster Brick-air cavity- Brick Plaster Primer	~27% reduction in thermal transmittance. ~1.5°C higher internal surface temperature. Reduced influence of thermal bridges.	[74,75]

	Evaluation of potential risks for condensation on the internal wall surfaces with and without AP.		1.2-1.5 cm of AP	~2 months were required to dry out the water initially in the mixture. No interior surface condensation at 60% internal RH- levels.	
Turin-Italy	Evaluation of thermal performance of AP under operating conditions.	52 cm brick	52 cm brick ~4.5 cm AP	~60% reduction in heat transfer coefficient. 21%[5]/ 17%[76] higher measured thermal conductivity of the AP than the declared value based on laboratory measurements, due to higher moisture content (further measurements ongoing).	[5,76]
Oslo- Norway	Evaluation of thermal performance of AP in the Norwegian climate. (As part of the FutureBuilt program [77].)	Plaster Brick Plaster	Lime-based paint 7 mm: reinforcement mortar + reinforcement mesh+ surface stabilizer 7 cm AP Undercoat mortar Brick Plaster Lime-based paint	~38% reduction in total net energy demand. Increased temperature in the external wall: reduced risk of crackling and moisture accumulation.	[78]

Table 17. Summary of reviewed full-scale studies on APs with respect to a selected number of criteria. “Y”: if the criterion is met. “N” if the criterion is not met. “P” if the criterion is partially met. “NS” if the criterion is not stated in the study. INT: Internal. EXT: External.

Criterion	[66] Nice	[67] Nice	[68] Nice	[69] Le Bourget du Lac	[70] Vienna	[71] Vienna	[72] Sissah	[63] Dällikon	[73] Berlin	[74,75] Turin	[5] Turin	[78] Oslo	Number of fulfilled criterion (Y)
Building type: façade material	Concrete	Concrete	-	Brick	Brick	Brick	Limestone	Concrete	Concrete	Brick	Brick	Brick	-
Type of AP: commercially available	N	N	N	NS	Y	Y	Y	N	Y	N	N	Y	5 out of 12
External/internal application of AP	EXT	EXT	EXT	EXT	EXT	EXT	EXT	EXT	EXT	INT	INT	EXT	-
Application method: spray machine	NS	NS	NS	NS	NS	NS	NS	NS	NS	N	N	Y	1 out of 12
AP thickness less than 5 cm	Y	Y	Y	NS	Y	Y	N	NS	N	Y	Y	N	7 out of 12
Reported improved thermal performance	Y	Y	P	P	N	Y	Y	NS	Y	Y	Y	Y	8 out of 12
Reported reduced U-value of façade by>50 %	N	N	N	N	N	Y	Y	NS	Y	N	Y	N	4 out of 12
Reported improved thermal comfort	N	N	N	N	Y	N	Y	N	N	Y	N	N	3 out of 12
Reported major damages	N	N	N	N	N	N	N	N	N	N	N	N	0 out of 12
Reported minor damages	N	N	N	N	N	Y	N	N	N	N	N	N	1 out of 12
Reported visible cracks	N	N	N	N	N	Y/N	N	N	N	N	N	N	1 out of 12
Reported usage of reinforcement mesh	N	N	N	N	N	N/Y	Y	Y	Y	N	N	N	4 out of 12
Reported reduced risk for moisture damage	Y	N	N	N	N	N	Y	N	N	P	N	Y	3 out of 12

4.3 Identified challenges with laboratory measurements

To better understand the performance of the fresh mortar and hardened AP, and to measure the material properties, not found in the literature, a set of laboratory measurements were conducted. The conducted laboratory measurements had the additional aim to evaluate the suitability of the selected test methods for AP. As explained in Section 2.3, standard test methods suggested by the European standards (Table 5) have been successfully used for APs in previous publications.

The conducted work in the lab, included sample preparations (mixing and curing) and measurements on thermal conductivity, thermal diffusivity and specific heat capacity, vapor permeability, capillary water absorption and moisture sorption isotherms. In Table 18, a list of the conducted measurements and the required samples are presented. In Appendix A, photos from the conducted measurements are provided.

In this section, the identified details and challenges regarding the preparation of the samples of AP are revealed. The quantitative analyses of the measurement results are not included in this thesis.

Table 18. List of the conducted laboratory measurements and the corresponding details of the samples.

Method of measurement	Measured material property	Sample: shape & dimension
Transient Plane Source (TPS) Method [8]	Thermal conductivity (W/(m·K))	Cubic: 10cmx10cmx10cm
	Thermal diffusivity (m^2/s)	
	Specific heat capacity ($J/kg \cdot K$)	Cylindrical: (D: 20mm, H:5 mm)
Wet cup method [9]	Water vapor permeability (-)	Cylindrical: (D: 100mm, H:20 mm)
Water suction test [10] (Gravimetric analysis)	Capillary water absorption ($kg/(m^2 \cdot min^{0.5})$)	Prisms: 40mmx40mmx160mm
Climate chamber method [11] (Gravimetric analysis)	Moisture sorption isotherm (-)	Quadratic: 100mmx100mmx~15mm

To conduct the described laboratory measurements, several sets of samples were prepared. Figure 7 shows photos from the process of mixing, casting and curing of the AP specimens. The process followed the instructions provided in the standards and the TDS of the AP product. Once the fresh mortar was molded, a curing campaign of 28 days under controlled conditions (T and RH) was initiated:

- Day 1-7: 20 ℃ and 95 % RH
- Day 8-28: 20 ℃ and 65 % RH

Figure 8, shows the prepared samples after the removal of the molds. During the attemps to prepare the samples of AP, it was noticed that the properties of the final product relied by a large degree on the details implemented during the preparation process. It was of great importance to follow the exact mixing schedule described by the producer. Any deviation could cause an undesired behaiviour of the final product. For the very first mixing attemps, the final product contained an unsually large amount of air voids and became too soft. This issue resultet in several failure attemps, as shown in Figure 9. In some cases, the detaching of the samples from the mold failed as some parts of the sample stuck to the interior surfaces of the molds. This issues occurred even when the internal surfaces of the molds were lubricated. In some other cases, the samples were damaged while removing the molds due to low mechanical strength.

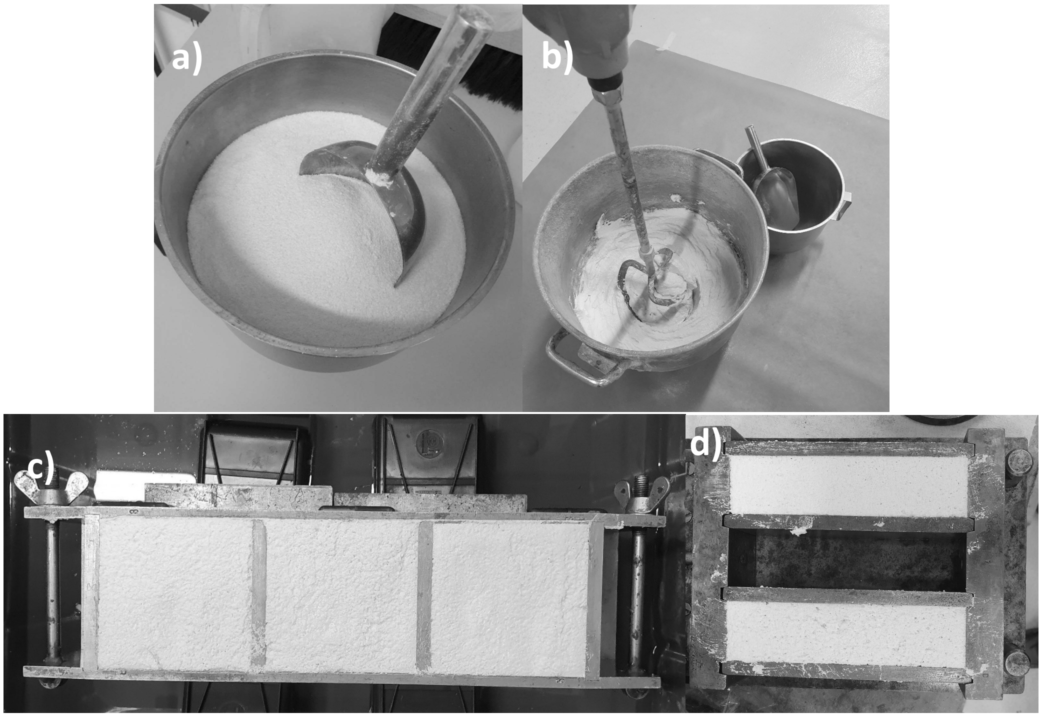

Figure 7. Photos showing the mixing, casting and curing of AP specimens. a,b) Mixing of fresh mortar of AP using a mechanical mixture. c,d) Casting of fresh mortar of AP in molds before curing in 28 days.

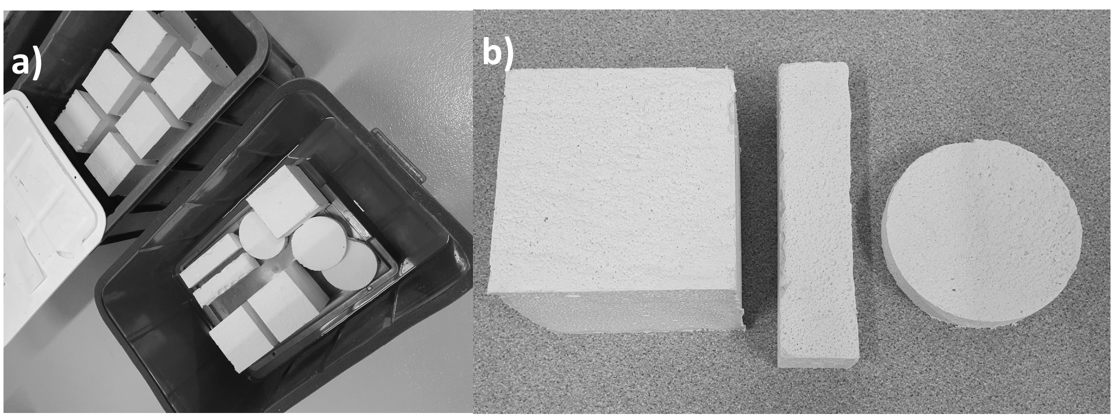

Figure 8. Photos showing the AP samples after removal of the molds. a) Samples after the first seven days of curing. b) Samples at the end of the curing period (28 days).

After contact with the producer, some of the details were adjusted and samples with less air voids and better performance were produced. Among others, the lab-mixture used in the process was replaced by a new mixture, shown in Figure 7,b. In addition to the samples of AP, the author prepared a number of samples from two conventional lime-based plasters. These issues and the level of sensitivity described for AP samples, were not experienced for the conventional plasters.

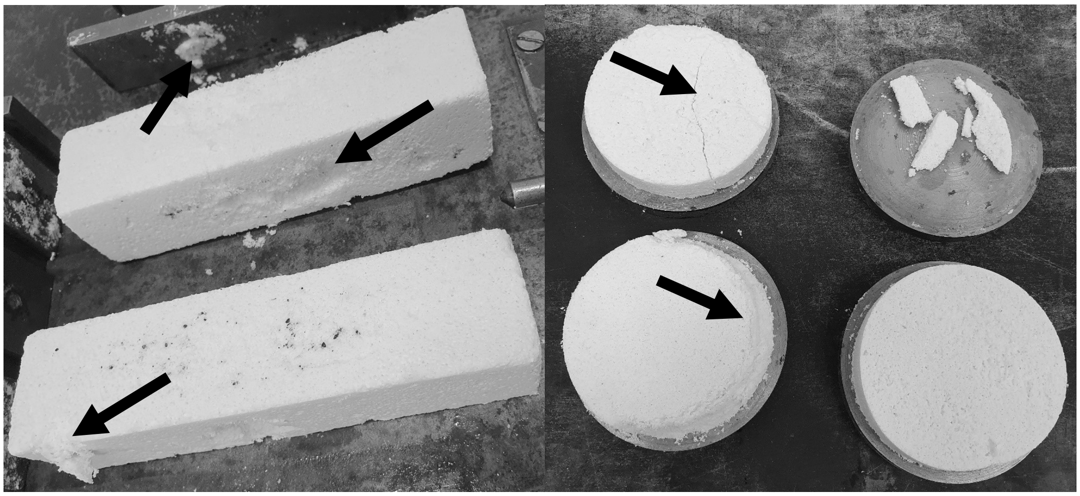

Figure 9. Photos showing examples of failures during the preparation process of AP samples. The arrows show the damaged parts of the samples.

During the laboratory trials with the wet cup method tests, an issue was noticed with the sealing of the AP samples. The surfaces of the specimen were dusty and unsusceptible for adhesion of waxes and butyl tapes, which are commonly used to make the specimens vapor tight at the cup edges. Figure 10 shows the attempts where the sealing of the APs failed. A solution to this problem was found by applying a layer of epoxy directly on the AP specimen before a butyl tape was placed.

Figure 10. Photos showing sealing attempts of AP samples for cup method test. Left: Detaching of the butyl tape from the surface of the AP sample. Right: Wax detaching from the surface of the AP sample.

Apart from the issues and challenges mentioned above, the selected measurement techniques for the characterization of AP sample, worked well. Results from the on-going measurements show that the standard methods used for conventional plasters can be used for APs. However, due to the presence of aerogel granules and the unique properties of APs compared to conventional plasters, the process of sample preparation and the measurements are more sensitive and thus require additional care for the details. The unique properties of APs include higher softness and lower mechanical strength, higher heterogeneity as well as higher porosity and lower thermal conductivity.

5 Conclusions and discussions

In this thesis, the possibilities and challenges associated with the applications of aerogel-based plasters (APs) in Sweden were evaluated. The methods used for this purpose were literature review, interview, study visit, numerical energy simulation and laboratory measurement. The focus of the study was on the hygrothermal and mechanical performance of APs and their compatibility with other materials when applied in multi-layer wall systems. From the literature review, the currently missing information on available APs, required to perform reliable risk assessments and advanced hygrothermal analysis, were mapped. Previous full-scale studies and accelerated aging studies of APs were reviewed to collect and summarize the available knowledge and experiences. The feasibility and energy saving potentials of APs in Swedish buildings, were studied by numerical energy simulations. Based on the interviews with Swedish experts and stakeholders, the important aspects and concerns that need to be addressed before APs can be introduced in Sweden were identified. The learnings from the study visit to a manufacturing company of a commercial AP and the conducted laboratory measurements were utilized to better understand the performance and application details of APs.

5.1 Conclusions

The energy calculations showed that covering façades with AP would increase the energy efficiency of building envelopes. In the reference building studied in this work, application of 5-15 cm AP reduced the U-value by 45-70 %. According to the study, a total energy of 74±48 GWh could potentially be saved annually in Sweden if 10 % of all the plastered multi-family houses would be renovated by APs.

Regarding the material properties of available APs, it was concluded that the existing sets of properties, necessary to conduct hygrothermal and mechanical risk assessment, are incomplete. Properties such as temperature and moisture dependent thermal conductivity, heat capacity, flexural and adhesive strength and sorption isotherms were completely or partially lacking. For the long-term durability of APs, the existing research is limited to a few studies on non-commercial APs. The long-term performance of APs needs to be further investigated before a conclusion can be made.

The full-scale studies on APs have shown promising results concerning the energy performance of APs. No failure or major issues have been reported in the reviewed scientific documents. However, the studies were limited to mainly Central European countries. Representative full-scale studies in cold, humid and windy regions with freeze-thawing, such as the climate in Sweden are limited. Regarding the compatibility of APs when combined with other building materials in multilayer plastering systems, a scientific guideline or standard on how to select and combine the materials, to obtain a proper and safe construction is lacking. There are, however, recommendations on selection of suitable materials from the manufacturers. No major issues concerning the compatibility of APs with other materials have previously been reported in the literatures.

Based on the interviews with the experts in the field, important aspects related to the possibilities and challenges associated with the introduction of APs in Sweden, were identified. The energy and space saving potentials of APs and their suitability to solve some of the challenges in the renovation of existing buildings were considered the major benefits of APs. Clear information and documentation from the manufacturer of APs was identified as prerequisites for APs to become trusted and accepted by the building industry. Reliable datasets with material properties and information on long-term durability of APs were considered as necessary to motivate the higher investment costs for APs. The economic benefits were also further highlighted as one of the criteria when deciding on introducing a new material or solution such as APs in a construction project.

5.2 Discussions and recommendations for future research

In the pre-study on the energy performance of APs presented in this thesis, the thermal properties of the AP were the declared values by the manufacturer. These declared properties are based on laboratory-based measurements under controlled conditions. However, the conditions in field are normally different. Also, the built-in moisture in the plastering system including the AP, will require a certain time, normally a few months or years, before it is dried out. Therefore, and as reported in some previous studies, a lower thermal performance can be expected on site than what is declared in the TDS of the product, at least during the early stages of the application of APs. In this study, the energy-saving potentials were calculated based on a conservative approach to somehow compensate for such unknowns and uncertainties at the time being. With a better knowledge about the moisture dependent thermal performance of APs during the early stages of the application, a more precise, and potentially less conservative, analysis can be performed.

So far, APs have not been tested in any building located in Sweden. For the future introduction of APs in Sweden, they need to eventually fulfill the requirements set by the Swedish building regulations. To answer all the questions related to the performance of AP, with respect to the Swedish climate conditions and building techniques, risk assessments are necessary. Without a reliable and complete set of material properties for APs, the evaluation of APs, according to the conditions defined in the regulations, becomes a complicated task. As a consequence, the introduction of APs in the Swedish building industry might be difficult as well.

Based on the results from the previously conducted full-scale studies on APs in countries other than Sweden, APs are considered as promising materials to be introduced and used in Swedish buildings. Apart from the obvious energy- and space saving potentials, APs may also be a possible solution for many complicated renovation cases. As mentioned in the thesis, renovations of historical and listed buildings include a number of challenges that in many cases require special solutions. APs have the potential to be a suitable contribution to solve some of these challenges. However, as these renovation cases are already difficult and challenging, it is important to fully evaluate the APs and identify the required conditions and procedures to achieve moisture safe and energy efficient renovations in Sweden.

Future work on the application of APs in Sweden should focus on the missing hygrothermal and mechanical properties of APs. These are needed to present a complete and reliable data set on APs to perform necessary risk assessment analyses. Also, the required conditions for APs to be combined with other materials when used in multilayer wall and plastering systems should be identified and systemized. As requested by the building industry in Sweden and to evaluate the performance of APs in Sweden, there is a large need for conducting full-scale studies on APs in Sweden. Apart from energy performance, focus of these full-scale studies should be on the hygrothermal and mechanical performance of APs to provide (moisture) safe solutions.

5.2.1 Future research within the project

In this section, the general thoughts of the author, regarding the focus of the research after the licentiate are presented. The discussion here, includes the main research questions that will be addressed, and the corresponding methodology intended to be used.

Based on the study presented in the thesis, a number of research gaps were identified. There are currently limited studies on the hygrothermal performance of APs in cold and wet climate regions such as Sweden. The information on hygrothermal and mechanical properties and long-term durability of APs need to be complemented. Also, the compatibility of APs with other materials when installed in multilayer wall configurations require more research.

As a contribution to fill the identified knowledge gaps about the performance of APs, the research will focus on different aspects of the hygrothermal performance of APs and their compatibility with other materials in multilayer wall systems. The research methods used and the specific goals of the studies are described in Table 19. Also, a more in detail list of the specified suboperations in the project is presented in Appendix B. The studies concerning the literature reviews and laboratory measurements were mainly conducted at the time of Licentiate. For the remaining time after the Licentiate and to evaluate the research questions specified, experimental studies and hydrothermal simulations will be combined:

- Full-scale measurements under realistic weather conditions in Sweden
- Pilot studies in laboratory: Laboratory-based measurements of multilayer plastering systems under controlled conditions
- Hygrothermal simulations: different building and climatic scenarios

Based on the outputs of the conducted studies, a guideline containing practical recommendations for the application of APs in Sweden will be developed. The recommendations will provide the necessary information on APs with focus on hygrothermal properties, to researchers, engineers, and decision makers. These information are intended to be used in future projects and evaluation processes, according to the Swedish building regulations, to provide safe renovation solutions with APs in Swedish buildings.

Table 19. The focus of the research within the project and the intended methodologies to be implemented.

<table>
<thead>
<tr><th>Method of research</th><th>Method description</th><th>Evaluated subjects</th></tr>
</thead>
<tbody>
<tr><td>Literature review</td><td>Review of previous research conducted on APs

Focus on hygrothermal and mechanical performance, and long-term durability</td><td>Identification of knowledge gaps

Information deficiency about APs necessary for (hygrothermal) risk assessments</td></tr>
<tr><td rowspan="2">Laboratory measurements under controlled climate conditions</td><td>Material characterization of AP</td><td>Hygrothermal and mechanical properties required for advanced hygrothermal calculations</td></tr>
<tr><td>Multilayer wall configuration including AP</td><td rowspan="3">Hygrothermal performance of APs in respect to Swedish climates and building conditions, combined with materials with different properties

Drying rate of initial built-in moisture during the application phase

Evaluation of moisture related risks during the application phase and the additional needs (if any) for additional protection measures when installed in Sweden (to avoid too sever conditions for APs, crack formation, etc.)

Moisture transport through a system of materials (including AP) with different hygrothermal properties: Threshold values on the relation between the hygrothermal properties of the materials combined with APs to avoid moisture damages

Moisture distribution in multilayer plastering systems (including AP) with and without cracks in the construction.</td></tr>
<tr><td>Numerical simulations</td><td>Performance evaluation of AP in different scenarios

Various material combinations

Various outdoor and indoor climate conditions</td></tr>
<tr><td>Full-scale measurements under realistic climate conditions in Sweden</td><td>1-2 full-scale case studies to evaluate the performance of AP

Focus on hygrothermal and mechanical performance</td></tr>
</tbody>
</table>

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Appendices

Appendix A: Laboratory measurements

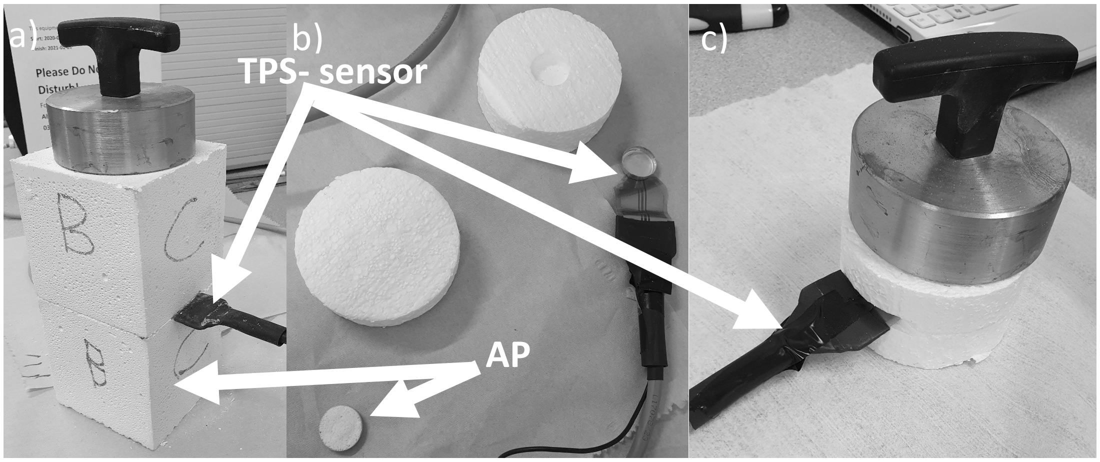

Figure 11. a) Experimental setup for TPS measurements: determination of thermal diffusivity (thermal conductivity and heat capacity). b,c) Separate TPS-measurement setup for determination of heat capacity.

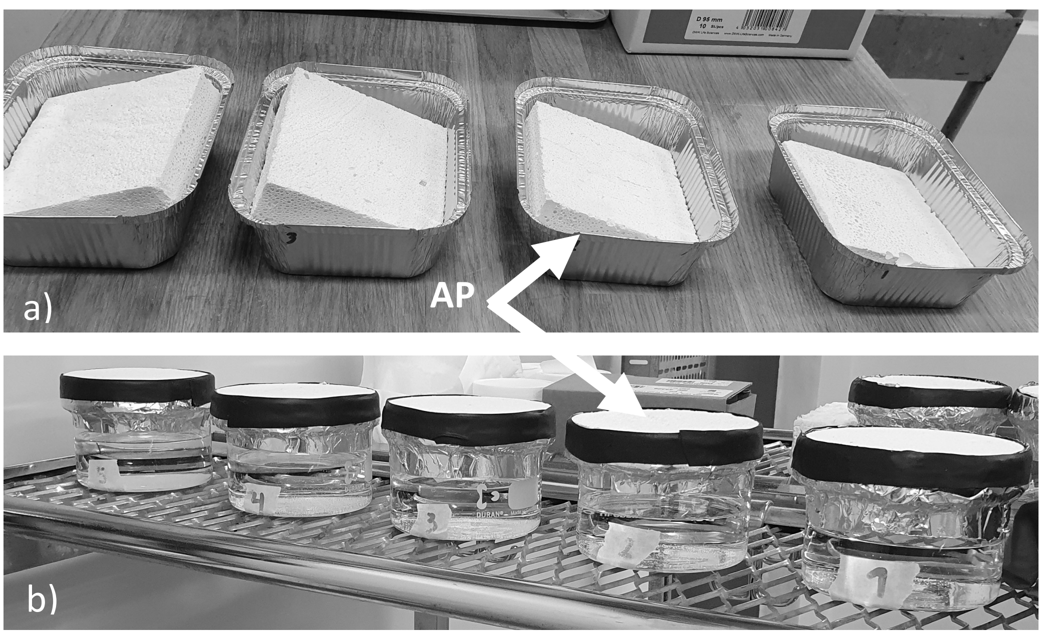

Figure 12. a) Prepared samples for the determination of moisture sorption isotherms of AP. b) Prepared cups for the determination of water vapor permeability coefficient of AP.

Appendix B: Specified suboperations within the research project

Table 20. List of suboperations within the research project and the corresponding additional information.

Suboperations in the research project	**Previous studies (Yes, No, Partly)**	**Included in the research (Yes, No, Partly)**	**Priority (1–3)**
Material properties			
Thermal properties		Yes	1
• Thermal conductivity	Yes		
• Specific heat capacity	Partly		
• Thermal diffusivity	Partly		
Moisture properties		Yes	1
• Vapor permeability	Yes		
• Capillary suction	Partly		
• Frost resistance	No		
Mechanical properties		Partly	3
• Compression strength	Yes		
• Tensile strength	Partly		
• Adhesive strength	No		
Characteristics		Partly	3
• Porosity	partly		
• Pore size distribution	Partly		
AP multilayer wall configurations			
Moisture/water transport through the system		Yes	2
• Layers with different hygrothermal properties	Partly		
• With respect to torrential rain	No		
• With respect to occurrence of cracks	No		
• Drying of (built-in) moisture	Partly		
• Ap and salt precipitation (Efflorescence)	Partly		
Deformation, Shrinkage, crack formation		Yes	3
• Application phase	No		
• Later stages: climatic strains	No		
	Partly		
Compatibility between AP and existing materials in the wall	Partly		
Full-scale: Hygrothermal performance			
		Yes	2
• With respect to Swedish constructions	No		
• With respect to Swedish climates	No		
• Internal application	Partly		
• External application	Yes		
Additional aspects			
• Long-term performance		No	-
• Life cycle assessment	Partly		
• Assessment by Swedish building regulations	Partly		
• Reversibility	No		
	No		