Knowledge gaps regarding the hygrothermal and long-term performance of aerogel-based coating mortars

Citation for the original published paper (version of record):
Karim, A., Johansson, P., Sasic Kalagasidis, A. (2022). Knowledge gaps regarding the hygrothermal and long-term performance of aerogel-based coating mortars. Construction and Building Materials, 314(Part A).
http://dx.doi.org/10.1016/j.conbuildmat.2021.125602

Construction and Building Materials 314 (2022) 125602

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Knowledge gaps regarding the hygrothermal and long-term performance of aerogel-based coating mortars

Karim Ali Naman*, Johansson Pär, Sasic Kalagasidis Angela

Department of Architecture and Civil Engineering, Division of Building Technology, Chalmers University of Technology, SE-41296 Gothenburg, Sweden

ARTICLE INFO

Keywords:
Aerogel
Coating mortar
Plaster
Render
Thermal insulation
Energy efficiency
Retrofitting
Renovation
Hygrothermal
Durability

ABSTRACT

Aerogel-based coating mortars are an emerging class of multifunctional wall finishes that stand out for their thermal insulation performance. Commercial and trial mixtures, studied under laboratory conditions, have a declared thermal conductivity of about 30–50 mW/(m•K). This is comparable to conventional insulation materials such as polystyrene and mineral wool. Aerogel-based coating mortars are primarily intended for use in existing and uninsulated building envelopes. Currently, there is a high research interest in the development of aerogel-based coating mortars. Nevertheless, the knowledge about their hygrothermal and mechanical properties have not been fully explored yet. These properties are needed to assess the moisture risks and long-term durability in different applications and to justify the higher investment costs for aerogel-based coating mortars compared to conventional ones. Apart from the material properties of aerogel-based coating mortars, results from full-scale studies focusing on hygrothermal performance are scattered and representative for limited number of climate conditions and specific products.

In this article, available information on hygrothermal and mechanical properties of aerogel-based coating mortars is collected and systematized. The aim is to map the missing data needed for moisture risk assessments. This study focuses on knowledge gaps regarding the hygrothermal and long-term performance of aerogel-based coating mortars, both commercial products and laboratory-based trial mixtures. In addition, economic perspective and health related concerns of the material are discussed. The results indicate that future research efforts should focus more on moisture risk assessments of the material to ensure moisture safe designs especially in areas with humid climates and freeze-thawing. More information needs to be readably available on the mechanical and hygrothermal compatibility of aerogel-based coating mortars with other materials in multilayer wall systems. In addition, available information on the hygrothermal and mechanical properties and long-term performance of aerogel-based coating mortars need to be further explored.

1. Introduction

Lately, attention has been focused on energy-efficient aerogel-based insulation materials [1–9], aiming at minimizing the energy use for space heating and, thereby, the environmental impact of buildings on energy systems. Due to their comparably high thermal insulation, these materials introduce new opportunities to increase the energy efficiency of buildings while achieving slimmer building envelopes. ACM are aerogel-incorporated plasters and renders with thermal conductivities (mW/(m • K)) of about 30–50 mW/(m • K). They are primarily intended for the retrofit of uninsulated building envelopes in existing buildings. The possibilities for using ACMs in building retrofits are theoretically enormous. In Europe alone, about 75 % of the existing buildings are not considered energy efficient [10] and in need of partial or deep renovations. An energy-efficient building envelope is often highlighted as an effective measure when retrofitting existing buildings [11]. However, this is not always a straightforward task. It involves a number of issues that need to be properly addressed to avoid costly and large-scale failures [12]. Issues related to the preservation of character-defining elements of listed buildings limit the possible renovation alternatives for building envelopes. Other concerns related to the compatibility of new

Abbreviations: ACM, Aerogel-based Coating Mortar; DSC, Differential Scanning Calorimetry; EPD, Environmental Product Declaration; GHP, Guarded Hot Plate; HFM, Heat Flow Meter; LCA, Life Cycle Assessment; MIP, Mercury Injection Porosimetry; MSI, Moisture Sorption Isotherm; TDS, Technical Data Sheet; TICM, Thermal Insulation Coating Moartar; UV, Ultraviolet Radiation.

* Corresponding author.
E-mail address: ali.karim@chalmers.se (A.N. Karim).

https://doi.org/10.1016/j.conbuildmat.2021.125602
Received 4 August 2021; Received in revised form 24 October 2021; Accepted 6 November 2021
Available online 18 November 2021

Nomenclature

A1	Fire class A1
A2	Fire class A2
A_{cap}	Capillary water absorption (kg/(m^2 · min$^{0.5}$))
c_p	Specific heat capacity(J/kg • K)
E_{dyn}	Dynamic Young's modulus (N/m^2)
FR	Fire Resistance (-)
P	Porosity (%)
RH	Relative Humidity (%)
T	(Air) Temperature (°C, K)
WVTR	Water Vapor Transmission Rate (g/h · m^2)
W	Moisture content (kg/m^3)
GREEK SYMBOLS	
μ	Water vapor permeability coefficient (-)
λ	Thermal conductivity (mW/(m • K))
λ(T)	Temperature dependent thermal conductivity (mW/(m • K))
λ(w)	Moisture dependent thermal conductivity (mW/(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)

building materials with existing constructions, restrictions on the admissible thickness of building envelopes, creation of thermal bridges and risks for moisture damage also add to the complexity of retrofitting existing buildings.

ACMs are intended to be used for retrofitting of uninsulated building envelopes in existing buildings to overcome some of the challenges mentioned above [12]. The focus of previous research studies on ACMs has been mainly on their thermal performance. Meanwhile, as demonstrated more in depth in Section 2.1, information on other properties such as mechanical and hygrothermal is less complete [13,14]. Like other newly developed materials, ACMs have higher investment costs compared to conventional coating mortars and insulation materials [15,16]. The economic perspective of ACMs is further discussed in Section 2.3. To motivate the higher investment cost of ACMs, it is necessary to minimize the uncertainties and unknowns associated with the application of ACMs in existing constructions with other building materials. This concern is particularly important in climates where moisture risk is high. To perform moisture risk assessments and prevent large-scale failures, it is a prerequisite to provide the entire supply chain, including decision-makers, designers, builders, researchers, and engineers, with a complete and reliable data set on the hygrothermal (heat and moisture) and mechanical properties, as well as the long-term durability of the contemporary ACMs.

The development of ACMs was initiated in the early 2010s [5]. The first article was published by Stahl et al. [5] in 2012, followed by studies on the material properties and full-scale application of the developed ACMs [17–19]. In parallel, works from other research groups have been published, focusing on the evaluation of existing ACMs or the development and characterization of new ACMs. Fig. 1 shows that research on ACMs has been simultaneously advanced by researchers in different countries. Research on ACMs has also been conducted within larger European collaboration such as the WALL-ACE project [20]. The focus of research on ACMs by researchers in different countries has varied. Some researchers developed and studied new types of ACMs with different compositions than the first one presented in [5]. Ibrahim et al. [21–24] studied different trial mixtures with different aerogel and xerogel granules, resulting in a patented product. In [7,16,25–27], a new set of trial mixtures, both for internal and external Applications, were investigated. The focus was on the development of ACMs with improved mechanical performance compared to the previous ACMs, without compromising their thermal performance. In [28,29], Júlio et al. analyzed a large number of trial mixtures with different material compositions. The focus was on the influence of different components on both hygrothermal and mechanical performance. Nosrati and Berardi [30,31], investigated the correlation between the proportion of aerogels in the mixture and the hygrothermal and long-term performance of ACMs. The analysis was performed by mixing conventional plasters with different fractions of aerogel granules. In the work presented by some other researchers, the focus has been mainly on evaluating the existing ACMs rather than developing new ACMs [18,32–35]. Apart from the research conducted on material-level, in-situ full-scale studies, laboratory pilot studies and hygrothermal numerical simulations have been carried out to evaluate the performance of ACMs in different climates and conditions.

Commercial ACMs have been available on the market since 2013 and have been used in buildings in Europe [36–44]. All available commercial ACMs consist of lime- and cement-based binders. However, they consist of different material compositions with different types of aggregates, aerogel granules, additives, admixtures, lightweight aggregates or filler. So far, ACMs have been used in several buildings in Europe, mainly in Central European countries, with promising results. In 2017, almost 200

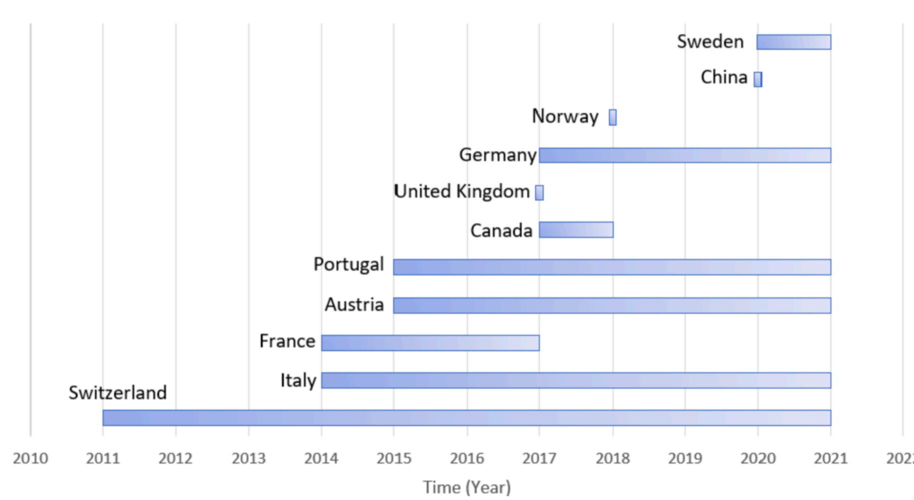

Fig. 1. Active years of publication for researchers in different countries working with ACMs. The dates are based on the year of submission of papers and not necessarily the year of publication.

buildings corresponding to 30000 m^2 of façade area were covered by ACMs [17]. In Europe and 2019, this number was increased to 100000 m^2 of façade area [45].

Because ACMs are attractive complements to traditional insulation materials for buildings, the number of trial ACM mixtures is increasing and thereby the need for an up-to-date and complete overview of their technical properties. Apart from this, the variation of commercially available ACM products in terms of material composition and performance adds to the complexity of this topic. For the purpose of directing further research on how to manufacture the ACM samples for laboratory tests and for applications in heritage buildings, Del Curto and Cinieri [46] compared thermal properties of selected trial mixtures of ACMs and a commercially available ACM. In [47], Lamy-Mendes et al. presented a review of silica aerogels and several silica aerogel-based materials. A section of the article was dedicated to aerogel-based mortars, including renders and plasters. Examples of trial mixtures and their properties, thermal conductivity, density, flexural and compressive strength, and results from some case studies were summarized. Similar to [46], it is concluded that future efforts should be directed towards the design of experimental trials. Otherwise, many experiments may be needed for optimizing the amount of aerogel in a mixture in respect to mechanical and thermal insulation properties of the final product. A recent review of Adhikary et al. [48] provides further insights in how the addition of aerogel particles affects the production and synthetization of different aerogel-based cementitious composites such as concrete blocks, plasters and renders. Durability, mechanical properties, pore size distribution, and water suction capability are also addressed. Finally, a summary of selected case studies on these cementitious composites, all based on research mixtures, and economic perspectives of aerogel were presented.

Based on the existing reviews [46–48], there is no detailed documentation or a literature review that compiles the available technical data of all ACMs, i.e. of both trial mixtures and commercially available products. Also, such a documentation on the details and results from all case studies regarding the implementation details and application domains for ACMs in different countries and different building types is missing. The aim of the article at hand is to address specifically the available and missing data on hygrothermal properties of all ACMs that are needed for moisture safe design of ACMs rendered building facades. Moisture safe design of building envelopes is identified by minimizing the moisture damage risks, which are estimated by various qualitative and quantitative tools. To conduct moisture risk assessment on ACMs, reliable and complete set of data on their hygrothermal, mechanical and long-term material properties is required. Also, their performance when applied on façades, together with other coatings and building materials need to be investigated for various building types and climate conditions. Despite the many similarities between the aerogel-based cementitious mortars addressed in e.g. [48] and ACMs, there are significant differences in terms of material composition, proportion of the components and the intended applications of the materials. For these reasons, other types of mortars than renders and plasters are not considered representative for ACMs and thus are excluded from this review.

1.1. Objectives of the work

This review article presents the state of the art of nearly a decade of research and development on ACMs. The aim is to identify the missing data on the contemporary ACMs, from a moisture risk assessment perspective, and to highlight the need for further research. In addition, a summary of available data on economic and health related concerns with ACMs is presented.

More specifically, the main objectives of the article are to compile and systematize the available knowledge on the following:

a. The main characteristics of different trial mixtures and commercialized aerogel-based coating mortars
   - Overview and availability
   - Testing techniques used to determine the properties of ACMs and their suitability
   - Provided and missing material properties and technical data
   - Long-term durability tests and performance of ACMs

b. The collected findings and implementation details from case studies on ACMs
   - Background, building types and results obtained in different full-scale, laboratory-based and simulation case studies
   - Application methods: technical details and strengthening techniques in the application of ACMs in field
   - Compatibility of ACMs with other building materials in multilayer wall system

1.2. Method of research

The collected information presented in this article is based on a systematic review of online references in English, including journal articles, proceedings and conference papers, books and book chapters, standards and websites.

Results for scientific references are based on searches in the databases "Scopus", "Web of Science" and "Google Scholar". Information on commercial products is collected from the websites of the manufacturing companies via the search engine of 'Google', but also from the data in published scientific papers. To ensure that all relevant data was included in the search, various combinations of keywords such as "aerogel plaster" and "aerogel render" were included in the search string. Further details of the search conducted are shown in Table 1. The search was limited to the period between 2012 and 2021 as the first paper on ACMs was published in 2012. The initial search based on the defined string in Table 1 and for "title, abstract and keywords" resulted in a large number of hits ($>$ 700). One possible reason for the high number of hits is that some other similar aerogel-incorporated materials [49,50], which are different from the defined ACMs in this article, are sometimes named with similar names used for ACMs. To better exclude the irrelevant hits where ACMs were not the focus of the work, the search was limited to articles that contained the keywords in their title. This significantly reduced the number of hits. Next, all articles that were not related to the topic of this paper, and duplicates from different databases were identified and excluded. A total of 61 published documents, 15 web sites and 17 standards were considered for the dataset of this article. The analysis of each entry was performed separately and based on the defined objectives of the article.

Table 1
Details of the search carried out to compile the final dataset of the work.

	Source	Searching area	Number of hits
Query string	**(aerogel *AND* plaster*) *OR* (aerogel *AND* render*) *OR* (aerogel *AND* coating mortar) *OR* (super *AND* insulation *AND* plaster*) *OR* (super *AND* insulation *AND* render*)**		
	Web of Science	Title, Abstract, Keywords	774
	Scopus	Title, Abstract, Keywords	600
	Google Scholar	Title, Abstract, Keywords	500
	Web of Science	Title	110
	Scopus	Title	98
	Google Scholar	Title	92
Final dataset			
	Published documents		61
	Web sites		15
	Standards		17
Total			93

2. Aerogel-based coating mortars: Plasters and renders

Aerogel-based mortars (ACMs), aerogel-based renders and plasters, are herein referred to as plasters and renders with incorporated aerogel granules [5] and a thermal conductivity below 100 mW/(m • K). Aerogels are classified as nanostructured Super Insulation Materials (SIMs) [51,52]. They include any type of material that is derived from molecular, organic, inorganic or hybrid compounds, also called precursors [1,2]. Aerogels are typically prepared by a multistep synthesis process that preserves the 3D network of the material with a high degree of porosity. Among 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 [15,48]. Table 2 shows relevant material properties for pure silica aerogels. High level of porosity, extremely low density and high surface area are some of the key properties that characterize aerogels in general [4,53]. The embodied energy of aerogels, the total energy that is used to produce one kilogram of aerogels, is 53 MJ/kg; a value in the same range as other conventional insulation materials. Untreated silica aerogels are hydrophilic [4,53] but their surface properties are normally modified to obtain hydrophobic properties [54,55]. Aerogels are very fragile materials due to their low mechanical strength [1]. Therefore, they are often used as a compound in aerogel-based composites such as ACMs.

In ACMs, a fraction of the aggregates (mainly sand) is replaced by aerogel granules, resulting in improved thermal performance compared to conventional plasters and renders [5]. Table 3, lists the typical thermal conductivities (λ , mW/(m·K)) used to classify plasters and renders. According to the European standard EN ISO 998–1 [58], plaster refers to the internal application of mortar, while render is when the mortar is applied externally. However, since most ACMs are for both interior and exterior application, they are sometimes referred to as plaster or render regardless of their interior or exterior application in previous publications. In this paper, any type of plaster or render with incorporated aerogel granules, and a thermal conductivity of less than100 mW/(m • K) is considered ACM.

In practice, ACM is applied on façades in a multilayer wall system consisting of several layers of mortars [59], see illustration in Fig. 2. generally, a thin layer of undercoat is applied prior to the ACM to increase the adhesiveness and sometimes to control the water suction to the substrate. The thickness of ACM, applied in one step, is normally limited to around 5 cm. Once the ACM has hardened, the coating system is supplemented by a layer of surface stabilizer, reinforcement mortar and in most cases reinforcement mesh. Finally, a layer of finishing mortar and in some cases water-repellent paint is added to the system. The total thickness of the coating system is increased by around 1–1.5 cm due to the additional layers applied together with ACM.

2.1. Material characteristics of ACMs

In this paper, the developed ACMs have been divided into two categories, each of which is reviewed separately. One category includes the trial mixtures developed and studied for research purposes. The second category includes commercialized ACM products. A total of 14 and 10 ACMs were identified and reviewed for the first and second categories, respectively.

Table 2
A selection of material properties for pure silica aerogel [15,56,57].

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 (mW/(m • K))	10–20
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

Table 3
Thermal conductivity ranges specified for the classification of coating mortars [5,58].

Type of coating mortar	Thermal conductivity (mW/(m • K))
Conventional coating mortar	$\lambda > 200$
Conventional thermal insulation coating mortar (TICM)	$\lambda < 200$
ACM	$26 < \lambda < 100$

For the characterization of ACMs, the European standard EN ISO 998-1 [58] contains the criteria for the classification of different types of coating mortars. It also specifies the standardized test methods for plasters and renders. A total of 16 standards [60–75] are specified in EN ISO 998-1 for the characterization of plasters and renders. In EN ISO 998-1, coating mortars with specific thermal insulation properties are classified as thermal insulation coating mortars (T1, T2), see Table 4. Based on this classification, ACMs belong to the T1 category. Table 4, shows some of the specified requirements for hygrothermal and mechanical properties of category T coating mortars.

Due to the presence of aerogel granules, ACMs have some unique properties compared to conventional coating mortars. These include higher softness and lower mechanical strength, as well as higher porosity and lower thermal conductivity. Based on the reviewed articles, standard test methods for conventional coating mortars have been used to characterize ACM. In Table 5, a list of the testing methods that have been reported in previous research articles are compiled. There was no reported need for major modifications of the test methods or any complications for testing ACMs. However, in on-going laboratory trials by the authors, major issues have been noticed with for instance the sealing of ACM samples for cup-tests. The cut surface of the specimen was dusty and unsusceptible for adhesion of waxes and butyl tapes, which are commonly used to make the specimens vapor tight at the cup edges, see Fig. 3. A solution was found by applying a layer of epoxy directly on the ACM specimen before a butyl tape was placed. Heterogeneity of ACMs and its effect on the measured properties at laboratory scale have not been addressed either, although one can expect that the addition of large proportions of hydrophobic aerogel granules in ACMs could increase the degree of heterogeneity. Whether the number and size of samples required by the standards for conventional coating mortars is also sufficient for ACMs with high proportions of aerogel can be questioned.

2.1.1. Trial mixtures

Trial mixtures refer to noncommercial blends of coating mortars and aerogel granules that are prepared for systematic investigations in laboratory environments. In Table 6 and Table 7, the main ingredients and properties of 14 selected trial mixtures are presented respectively, based on the publications from the following countries: Switzerland [5,17], France [23], Italy [7,12,16,27], Canada [30,80], Portugal [28,29,83,95–97], United Kingdom [81] and China [77]. To facilitate the reading, each trial mixture is marked by a unique term composed of the country abbreviation, followed by the name or location of the research laboratory that published the information. If necessary, a third term is introduced to provide additional details. The total number of reported trial mixtures in the cited articles was more than 14 because some of them represent a group of mixtures whose properties evolved between publications. As shown in Table 7, some trial mixtures were reported in different articles with different material properties. These property discrepancies could be due to changes in the composition of the developed trial mixtures, different properties of the raw materials or due to uncertainties in the measurements. However, these deviations were neither explained in the articles nor confirmed by the authors of the articles.

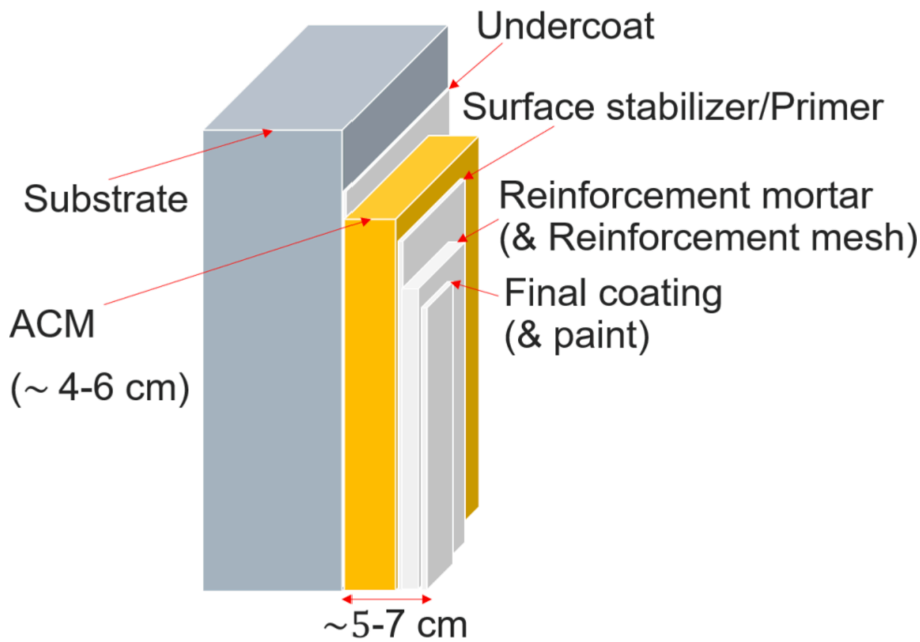

Fig. 2. Schematic, not in scale, showing the different layers of a multilayer wall system including ACM.

Table 4
Selected requirements for hardened thermal insulation mortar (T) specified in EN ISO-998–1 [58].

Material property	Symbol	Category	Requirement
Thermal conductivity (mW/(m·K))	λ	T1	≤ 100
		T2	≤ 200
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

While Table 7 summarizes all properties of the trial mixtures that were presented in the cited articles, Table 8 evaluates their hygrothermal properties based on the minimum requirements for advanced hygrothermal simulations as suggested by Fantucci et al. [7]. Apart from properties presented in Table 7, other properties such as specific surface area and pore structure of the ACMs were also studied for some trial-mixture [13,14,28]. The porosity of the trial mixtures stated in Table 7 are based on the information provided in the reference article. For cases where the specific type of porosity is explicitly stated in the reviewed article, the information is given in Table 7. As shown in Table 7, in 12 out of 14 trial mixtures, different types of mineral, lime or cement-based binders were mixed with silica aerogel granules and some other additives. The trial mixtures had densities ranging from 120-625 kg/m^3 and thermal conductivities from 14 to 85 mW/(m • K). The On average, data were missing for 4 out of 8 evaluated material properties considered in Table 8. Correct information on temperature and moisture dependent thermal conductivities, specific heat capacity, capillary water absorption and moisture sorption isotherms was more often missing. Information on moisture dependent thermal conductivity and capillary water absorption were not published in 14 and 13 of 20 articles, respectively. In addition to the parameters evaluated in Table 8, the mechanical properties, compressive and tensile strength, were also published less frequently. Among the studied articles, the mechanical properties were partially published only for 5 trial mixtures, with large discrepancies. Therefore, the mechanical performance of these trial mixtures needs to be further explored. The lack of sufficient details on the material properties of developed ACMs has been pointed out in previous studies [13,14] as well. The presented trial-mixtures are in many cases under development and thus rather likely that their material properties will be updated and publicly available in future.

2.1.2. Commercial ACMs

To pursue an objective comparison, the review of commercially available ACMs is limited to those whose technical data sheets (TDSs) are published online. In total, 10 commercial ACM products were identified and grouped by their ingredients and properties in Table 9 and Table 11 respectively.

The content of Table 9 and Table 11 is based exclusively on the information contained in the declared TDS for the product in question.

For the commercial ACMs reviewed, the current availability of some products that appeared in the literature could not be fully confirmed. According to RÖFIX [37] and [10], in addition to the product FIXIT 222, there was another ACM from the same manufacturer, FIXIT 244. However, at the time of writing, the product FIXIT 244 was not included in the online product list of the producer. The same applies for Interbran Premium 028 from Germany, mentioned in both [40], from 2017 and in [16] from 2019. One possibility is that this ACM has been further developed and replaced by XERAL SP 028 [41], XERAL SP 036 [42] and XERAL SP 055 [43], which were developed by the same manufacturer.

In addition to the commercial ACMs presented in Table 9, Fenoglio et al. [12] reported that a number of commercial ACM products have been developed in collaboration with industry partners although not yet fully launched in the market. A list of these products and their properties is presented in Table 10.

Similar to the analysis done for the trial mixtures, the commercial ACMs are evaluated based on the minimum requirements for available technical data for advanced hygrothermal simulations suggested by Fantucci et al. in [7]. The results of the evaluation are presented in Table 12.

As shown in Table 9, all 10 commercial ACMs consisted of (white) cement and various lime-based binders mixed with aerogel granules and various types of additives. All but two of the ACM products were for both interior and exterior applications. The commercial ACMs had thermal conductivities between 26 and 52 mW/(m•K) at densities between 180 and 290 kg/m^3. Based on the analysis presented in Table 12, there was on average no reported data on 4 of 8 material properties considered. Data on temperature and moisture dependent thermal conductivities, specific heat capacity and moisture sorption isotherms were most

Table 5
Compiled list of all properties and laboratory test methods used for the characterization of ACMs in previous publications. Blank cells indicate cases where the test method was not reported or when no standard for the test method was cited in the reference article.

Property	Testing method	Used standard	Article
Thermal conductivity (λ)			
	Guarded Hot Plate (GHP)	EN ISO 12,667 [76]	[5,17,21–24,77]
	Heat Flow Meter (HFM)	EN ISO 12,667 [76]	[16,21–26]
	HFM	ASTM C518-10 [78], ISO 8301 [79]	[27,31]
	HFM	–	[30,80,81]
	HFM (Transient test method)	ASTM D5930-9 [82]	[6,28,83]
Specific heat capacity (c_p)			
	Differential scanning calorimetry (DSC)	EN ISO 1159 [84]	[21–24]
	HFM	–	[7,16,85]
Density (ρ)			
	gravimetric procedures	EN ISO 1602 [86]	[21–24]
	gravimetric procedures	–	[16,26,29]
	gravimetric procedures	EN ISO 1015–10 [73]	[6,83]
Porosity (P)			
	Gas pycnometerMercury Injection Porosimetry (MIP)	EN ISO 8130–2 [87]-	[21][6,77]
Pore structure, specific surface area			
	Nitrogen sorption isotherm	–	[13]
Moisture sorption isotherm (MSI)			
	Climate chamber method (Gravimetric, in a sequentially changed and controlled environment)	EN ISO 12,571 [88]	[21,30]
	–	–	[19]
Water vapor permeability (μ , WVTR)			
	Cup method	EN ISO 12,086 [89]	[5]
	Cup method	EN ISO 12,572 [90]	[21,24]
	Cup method	EN ISO 1015–19 [64]	[6,28,81]
	Water vapor transfer method (WVT)	ASTM E96 [91]	[30]
Acoustic behavior			
	Kundt's tube Apparatus	EN ISO 10534–2 [92]	[27,93]
Flexural and compression strength			
	Three-point loading and compressive loading machine	EN 1015–11 [74]	[16,26,28,81]
Dynamic Young's modulus			
	Resonant frequency test	ASTM E1876-1 [94]	[28]

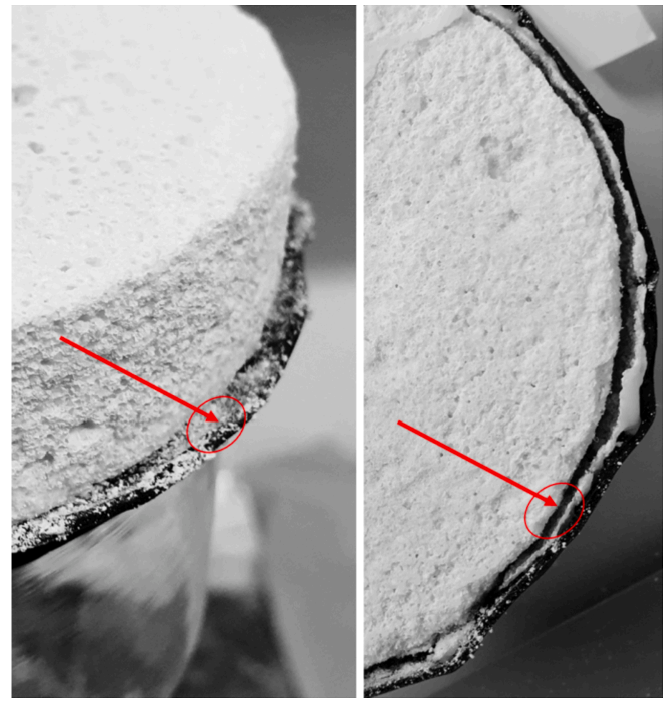

Fig. 3. Photos showing sealing attempts of ACM samples for cup method test. Left: Detaching of the butyl tape from the ACM sample. Right: Wax detaching from the ACM sample.

frequently missing. None of the manufacturers provided data on moisture dependent thermal conductivity or specific heat capacity. Regarding the mechanical properties of commercial ACMs, 8 of 10 manufacturers provided the compressive strength of the material. However, information on tensile and adhesive strength was not provided.

2.2. Long-term performance of ACMs

Aerogels, and ACMs in particular, have been commercially available in the construction industry for a relatively short time compared to other building materials [101]. 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 [102]. 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 [103].

In an accelerated aging test, the specimen is exposed to extreme conditions for a short time [103]. 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.

In [101], Karim et al. presented a review of previous studies dealing with the long-term performance of silica, silica aerogels and a number of

Table 6
List of trial mixtures reported in the published research articles.

Country	Abbreviated term	Ingredients	Ref.
Switzerland	CH-Empa	Hydrophobized silica aerogel, Mineral binder, additional additives	[5]
Switzerland	CH-Empa-b	Hydraulic lime, Hydrated lime, Aerogel (SiO_2), Mineral aggregates, White cement, Water retaining agent, Air entraining agent, Hydrophobic agent	[17]
France	FR-MINES	Mineral and/or organic hydraulic binder, Hydrophobic silica aerogel, Structuralizing filler (option), Additives (option)	[23]
Canada	CA-Ryerson-90	High performance hydraulic lime-based plaster, Hydrophobic silica aerogel (25–90 vol%)	[30]
Italy	IT-Perugia-99	High performance natural plaster, silica aerogel (80–99 vol%)	[27]
Italy	IT-Torino	Mineral and organic binders, Kwark aerogel (and other mineral light weight aggregates)	[16]
Italy	IT-Torino-50	Mineral and organic binders, Kwark aerogel (and other mineral light weight aggregates)	[7]
Portugal	PT-Lisboa-H	Portland cement as binder, Hybrid silica aerogel- or sand as aggregates	[29]
Portugal	PT-Lisboa-B	Mineral binders, rheological-, hydrophobic- agents, resins, lightweight fillers, commercial supercritical hydrophobic hybrid silica aerogel, thermal insulation aggregates	[95]
Portugal	PT-Lisboa-60	A cement-fly ash binder, silica aerogel, expanded cork, expanded clay, perlite	[28]
Portugal	PT-Lisboa-CA	A cement-fly ash binder, silica aerogel, surfactant, cellulose ether, resin	[13]
Portugal	PT-lisboa-37	Cement-based binder, rheological agent, resin, hydrophobic agent, hybrid silica aerogel	[6,14]
United Kingdom	UK-Bath-50	Lime putty as binder, sand and silica aerogel as aggregates,(Polypropylene fibers as secondary additive)	[81]
China	CH-Xi'an-64	Cement-based binder, hollow glass microsphere, silica aerogel	[77]

aerogel-based composites. For aging studies on ACMs, five papers were identified. The impact of accelerated aging on the thermal conductivity of trial mixtures of ACMs (CA-Ryerson) and other aerogel-based materials such as blankets and boards were presented in [31,104], see Table 13 and Table 14. 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 coating mortars [27]. 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.

For all CA-Ryerson mixtures, the thermal conductivity was increased after the aging tests. However, the magnitude of the increase was different for different aging factors and different ACMs. A general trend that could be observed was that the increase of thermal conductivity became less noticeable for ACMs with higher proportions of aerogel. The sample with no aerogel was the one that changed its properties most after the aging test. Among the different aging factors, relative humidity tended to have a high influence on the long-term performance of all samples. According to the authors [31] and based on naked-eye observations, minor cracks appeared on some of the specimens when aging was due to increased relative humidity and freeze–thaw cycles.

In [105], Frick et al. presented the very results of an ongoing large-scale accelerated aging study on the ACM product Quick-Mix. The study was later updated with the final results in [106].The test setup used in this study consisted of a rectangular chamber and four external walls whereof the two longitudinal walls were coated on the inside with a conventional coating mortar and with the Quick-Mix, respectively. The coated surfaces were exposed to a different number of weather cycles as shown in Table 14. Results from the evaluation of adhesion, water adsorption and visual inspections showed significant moisture uptake and up to 60 % reduction in the adhesion of the tested ACM.

In a recent aging study, Maia et al. [107] studied the long-term performance of a ACM through accelerated aging. ACM samples were exposed to several aging cycles of heating-freezing, freeze-thawing and heat-cold. According to the results obtained, the mechanical strength, apart from adhesive strength, was reduced. The highest reduction in mechanical strength occurred after freeze-thawing. The dynamic modulus of elasticity of the samples was reduced due to aging while the Poisson's ratio was increased. In another study conducted in Portugal, Morgado et al. [108] conducted several accelerated aging studies on a trial mixture of ACM. The ACM samples were exposed to several cycles of freeze-thawing, hygrothermal and infrared radiation and their thermal conductivity and mechanical strength was measured before and after the aging tests. In this study, the thermal conductivity was reduced, and compressive strength was increased after freeze–thaw cycles; results not completely in line with the results obtained in other accelerated aging studies on ACMs. Inappropriate dosage of surfactants in the mixture was suggested by the authors [108] as a possible explanation for the reduced weight loss and the unexpected results obtained after aging cycles.

In summary, the long-term performance of ACMs was evaluated in five articles using accelerated aging tests. These studies reported changes in the performance of ACMs such as increased thermal conductivity, up to 17 %, and decreased adhesive strength up to 60%. In one study [108], the thermal conductivity and compressive strength of the ACM was increased instead. None of the studies involved currently available commercial ACM products. The latter contain some additional additives, such as hydrophobic, air-entraining or water-retaining agents, which may be absent in the studied samples. The impact of these additives on the long-term performance of the ACMs is thus unknown. For these reasons, but also due to the limited number of studies evaluating the long-term performance of ACMs [48,108], it is not possible to assess whether the available long-term durability results for trial mixtures can be considered fully representative of the commercially available ACMs. It is worth to be mentioned that the current accelerated aging tests and the methods used for estimation of real-life exposure based on these tests are developed and validated for conventional materials originally. As such, the accuracy and reliability of these correlation methods between accelerated aging tests and real-life aging of ACMs can be questioned.

2.3. *Economic perspective of ACMs*

In this section, studies evaluating the cost-performance relationship of several thermal insulation coating mortars (TICMs) and ACMs are reviewed. In 2014, Barbero et al. [109] presented a comparative study between several TICMs available on the European market. The analysis focused on the thermal performance of the studied products and the corresponding costs. According to the technical analysis in [109], the optimal density for new and high energy efficient TICMs on the European market should be below 250 kg/m^3. For the economic analysis, the price was calculated for the total amount of each product required to achieve a thermal resistance of 1 (m^2·K)/W as shown in Fig. 4. A similar analysis for FIXIT 222 was presented two years later (2016) in [97] but it is not clear whether it was based on the prices from 2014 or 2016.

According to Fantucci et al. [16], the material cost of FIXIT 222 in 2019 was approximately 30 € per 1 m^2 surface area with a thickness of 1 cm (30 €/m^2/cm). Including the additional costs associated with the application process, the total cost was estimated at 60 €/m^2/cm. According to the updated price list for 2020 available from [110], the

Table 7
Compiled list of reported material properties for the developed trial mixtures presented in the reviewed research articles.

Product	ρ (kg/m^3)	P(%)	c_p(J/kg•K)	λ (mW/(m•K))	σ_c (N/mm^2)	σ_t (N/mm^2)	A_{cap} (kg/(m^2•s$^{0.5}$))	w(kg/ m^3)	μ -value(-)	FR	Ref.
CH-Empa	200	–	–	25 ± 2	–	–	–	–	4	–	[5]
CH-Empa-b	–	–	–	28	–	–	–	3.54 (at 50% RH)	4	A2	[17]
CH-Empa-b	200	–	–	27	–	–	0.032	2.55 (at 50% RH)	4	–	[19]
CH-Empa-b	–	–	–	29	–	–	–	–	–	–	[32,98]
FR-Mines	200	–	1100	27	–	–	–	–	–	–	[23]
FR-Mines	156	98	990 ± 5%	27±3%	–	–	0.184±15%	–	4.25±6%	–	[21]
FR-Mines	120	–	990	26	–	–	–	–	–	–	[22]
FR-Mines	156	–	990	26	–	–	–	–	4.25	–	[24]
FR-Mines	120	–	990	27	–	–	–	–	4.25	–	[99]
CA-Ryerson-90	200	–	–	27	–	–	–	–	–	–	[30]
IT-Perugia-99	115–125	–	–	14–16	–	–	–	–	–	–	[27,100]
IT-Torino	326	–	1070	51	–	0.8	–	–	–	–	[16,26]
IT-Torino-50	139	–	–	24	–	–	–	–	–	–	[7,25]
PT-Lisboa-H	412	–	–	85	–	–	–	–	–	–	[29]
PT-Lisboa-B	178	–	–	34	0.147		0.003	–	–	–	[95]
PT-Lisboa-60	652	–	–	84	0.92	0.16	0.23	–	16	–	[28]
PT-Lisboa-CA	418	71.8 (apparent)	–	66	0.47	–	0.06	–	14	–	[13]
PT-Lisboa-37	160	84.2 (open)	669	29	0.227	0.099	0.13	6 (at 80 % RH)	(7.8), 14.8	–	[6,14]
UK-Bath-50	652	–	–	50	–	–	–	–	–	–	[81]
CH-Xi'an-64	233	–	–	55	–	–	–	–	–	–	[77]
Maximum	625	98	1100	85	0.92	0.8	23	3.54	16	–	
Minimum	120	71.8	669	14	0.147	0.099	0.003	2.55	4	–	
Mean	258	84.6	971	38	0.44	0.353	3.9	3.045	7.7	–	
Median	200	84.2	990	27	0.35	0.16	0.095	3.045	4.25	–	

Table 8
Evaluation of the reported technical data for each trial mixture according to the list of minimum required technical data presented in [7]. "Y" if the correct data is reported. "N" if the data is not reported. "P" if the data is partially reported.

Product	ρ_{dry}(kg/m^3)	$\lambda_{10,dry}$(mW/(m•K))	c_p(J/kg•K)	μ -value (-)	A_{cap}(kg/(m^2•s$^{0.5}$))	λ(T) *(mW/(m•K))	λ(W) **(mW/(m•K))	MSI***	Number of non-reported parameters (N)	Ref.
CH-Empa	P	N	N	Y	N	P	P	N	4 out of 8	[5]
CH-Empa-b	N	N	N	Y	N	P	Y	Y	4 out of 8	[17]
CH-Empa-b	P	N	N	Y	Y	P	N	Y	3 out of 8	[19]
CH-Empa-b	N	N	N	N	N	P	N	N	7 out of 8	[32,98]
FR-Mines	P	P	Y	N	N	P	N	N	4 out of 8	[23]
FR-Mines	P	P	Y	Y	Y	P	Y	Y	0 out of 8	[21]
FR-Mines	P	P	Y	N	N	P	N	N	4 out of 8	[22]
FR-Mines	Y	P	Y	Y	N	P	N	N	3 out of 8	[24]
FR-Mines	P	N	Y	Y	N	P	N	N	4 out of 8	[99]
CA-Ryerson-90	P	P	N	P	N	Y	Y	Y	2 out of 8	[30]
IT-Perugia-99	P	N	N	N	N	P	N	N	6 out of 8	[27,100]
IT-Torino	Y	Y	Y	N	N	Y	N	N	4 out of 8	[16,26]
IT-Torino-50	Y	N	N	N	N	P	N	Y	5 out of 8	[7,25]
PT-Lisboa-H	P	N	N	N	N	P	N	N	6 out of 8	[29]
PT-Lisboa-B	P	N	N	N	Y	P	N	N	5 out of 8	
PT-Lisboa-60	P	P	N	Y	Y	P	N	N	3 out of 8	[28]
PT-Lisboa-CA	P	P	N	Y	Y	P	N	N	3 out of 8	[13]
PT-Lisboa-37	Y	Y	Y	Y	Y	P	Y	P	0 out of 8	[6,14]
UK-Bath-50	P	N	N	P	P	P	N	N	4 out of 8	[81]
CH-Xi'an-64	Y	P	N	N	N	Y	Y	P	3 out of 8	[77]
Number of products not reporting data on the parameter (N)	2 out of 20	10 out of 20	13 out of 20	9 out of 20	13 out of 20	0 out of 20	14 out of 20	13 out of 20	(On average) 4 out of 8	

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

Table 9
List of identified commercial ACM products.

Product	Country	Internal/ External Application	Ingredients	Ref.
FIXIT 222	Switzerland	Both	Hydraulic lime NHL 5, calcium hydroxide, white cement, aerogel granules, light mineral aggregate, water retaining agent, air-entraining agent, hydrophobic agent	[36]
FIXIT 244	Switzerland	Both	Hydrated lime, white cement, aerogel granules, light mineral aggregate, Organic components, Additives to improve the processing properties	[37]
HAGATHERM Typ Aerogel 402	Switzerland	Both	Hydraulic lime, hydrated white lime, white cement, aerogel granules, light aggregate, water retaining agents, air entraining agents, water repellent agents	[38]
HECK AERO iP WA	Germany	External	White cement, hydrated lime, aerogel granules, mineral lightweight aggregates	[39]
HECK AERO iP OWA	Germany	Internal	White cement (chromate-free), hydrated lime, aerogel granules, mineral lightweight aggregates	[39]
Interbran Premium 028	Germany	Both	Calcium hydroxide, cement, silica granules, perlite	[40]
XERAL SP 028	Germany	Both	Calcium hydroxide, cement, silica granulate, perlite	[41]
XERAL SP 036	Germany	Both	Calcium hydroxide, cement, silica granulate, perlite	[42]
XERAL SP 055	Germany	Both	Calcium hydroxide, cement, silica granulate, perlite	[43]
Poraver	Germany	Both	White cement, Natural hydraulic lime NHL 5, Poraver (expanded glass granule), aerogel, air entraining agent, Cellulose Ether, Dispersion Powder based on vinyl acetat and ethylene, starch Ether	[44]

Table 10
A list of ACMs reported in [12,20].

Product/Producer	Internal/External Application	ρ (kg/m^3)	λ (mW/m·K)
Quick-Mix	External	203	27
Vimark	Internal	136	27
Vimark	Internal (coating finishing)	136	28
Toupret	Internal patching filler	193	34

material cost for FIXIT 222 was 170 CHF for a 10 kg bag. With a material consumption of approximately 2 kg/m^2/cm and the current exchange rate, the material cost for FIXIT 222 in 2020 can be estimated to approximately 32 €/m^2/cm.

In [22], Ibrahim et al. conducted a cost analysis to study the optimal thickness and the corresponding payback period for the FR-MINES in different climates and cities, see Fig. 5 and Fig. 6. The optimal thickness was calculated based on the annual heating energy demand in kWh, material and electricity cost of the ACM, present worth factor and heating set-point for an uninsulated house built before 1974. The analysis was performed for the cities of Nice, Bordeaux, Strasbourg, Stockholm, Montreal and Moscow. The same electricity cost of 0.13 €/kWh was considered for all cities. In the calculations presented, a service lifetime of 40 years, an interest rate of 2.5 % and an inflation of 2 % was assumed. The heating set-point was set to 19 ℃ and the material cost in the reference case was set to 800 €/m^3.

In another study conducted in Portugal, an energetic and economic life cycle assessment, Cradle to Cradle (2E-C2C), of several TICMs and non-commercial ACMs was performed by Garrido et al. [111]. In total, 25 trial mixtures with various compositions and various types of commercial and non-commercial aerogels were studied. The thermal conductivity of the studied TICMs and ACMs were between 60 and 900 mW/(m^2·K). The energy use and cost of heating of an apartment in an uninsulated brick building in Seixal were used as a case study to evaluate the energy performance and economic benefits of the studied products. The analysis only considered the costs and energy savings from the application of TICMs and non-commercial ACMs. The energy retrofit strategies included the application of 4 cm of each TICM and ACM on the exterior, interior or both sides of the façades. From the analysis, it was concluded that for a 30-year lifetime, none of the renovation cases could be economically motivated.

For the commercial ACM product FIXIT 222 [36], a LCA (Cradle to gate) was conducted in 2015. The results were presented in an Environmental Product Declaration (EPD). The energy payback period of the product was also calculated to be approximately 2.9 years. The calculated value corresponded to the application of 5 cm of the product on a standard brick wall.

As noted, the studies regarding the cost versus energy performance of ACMs were limited to three case studies on few ACMs and for few climate conditions. Considering the payback period for ACM, the case study presented in [22] suggested a pay-back of 1.4 to 2.7 years, for four countries and seven cities. Also, the payback time calculated for the ACM product in [36] was stated to be around 2.9 years. The calculated payback periods seem to be in the same range and around 1–3 years. However, due to the limited number of case studies, more research is needed before these values can be considered or extrapolated for other ACM products and other countries and climates. Thanks to the higher thermal insulation of ACMs compared to conventional plasters, the application of ACMs increased the possibility of creating slimmer building envelopes. At the same time, the higher cost of ACMs compared to other TIPs was highlighted in these studies. Further investigations are needed to fully evaluate the economic performance of ACMs. Apart from the direct costs and energy savings associated with ACMs, other aspects such as possibilities to increase inhabitable space through slimmer building envelopes, reduced risks of moisture damage, improved thermal comfort and more suitable alternatives for the renovation of listed buildings should also be included in such analyses.

2.4. Health-related consideration of ACMs and aerogels

Potential health, toxicity and environmental aspects of nanomaterials such as aerogels, have lately been intensively studied by researchers around the world [1,112]. For aerogels, nanotoxicity is a relatively new field with many unknown effects. In a study presented by Nel et al. [113], the toxicity of amorphous silica was investigated. In this study, it was concluded that amorphous silica is generally safe to use.

Table 11
Compiled list of reported material properties of commercial ACMs.

Product	$\rho(kg/m^3)$	P (%)	c_p(J/kg •K)	$\lambda(mW/(m•K))$	$\sigma_c(N/mm^2)$	$\sigma_t(N/mm^2)$	$\sigma_{ad}(N/mm^2)$	$A_{cap}(kg/(m^2•s^{0.5}))$	μ -value (-)	FR	Ref.
FIXIT 222	220	90	–	28	0.45	–	–	- (W1)	4–5	A2	[36]
FIXIT 244	290	–	–	48	–	–	–	–	6	–	[37]
HAGATHERM Typ Aerogel 402	220	≥ 20	–	28	0.45	–	0.08	- (W1)	4–6	A1	[38]
HECK AERO iP WA	180	–	–	34.5	0.5	–	–	≤ 0.2 (W2)	≤ 5	A2	[39]
HECK AERO iP OWA	180	–	–	36	0.5	–	–	≥ 0.4 (W0)	≤ 5	A2	[39]
Interbran Premium 028	200	–	–	28	0.8	–	–	0.008–0.033	6	A2	[40]
XERAL SP 028	200	–	–	26	0.4	–	–	- (W1)	5	A2	[41]
XERAL SP 036	220	–	–	34	0.4	–	–	- (W1)	5	A2	[42]
XERAL SP 055	240	–	–	52	0.4	–	–	- (W1)	4	A1	[43]
Poraver	200	45	–	38	–	–	–	–	–	–	[44]
Maximum	290	90	–	52	0.8	–	0.08	–	6	–	
Minimum	180	45	–	26	0.4	–	0.08	–	4	–	
Mean	215	67.5	–	35.3	0.49	–	0.08	–	5.05	–	
Median	210	67.5	–	34.3	0.45	–	0.08	–	5	–	

Table 12
Evaluation of reported technical data for each commercial ACM according to the list of minimum required technical data presented in [7]. “Y” if the correct data is reported. “N” if the data is not reported. “P” if the data is partially reported.

Product	$\rho_{dry}(kg/m^3)$	$\lambda_{10,dry}(mW/(m•K))$	c_p(J/kg •K)	μ -value (-)	$A_{cap}(kg/(m^2•s^{0.5}))$	λ(T) *(mW/(m•K))	λ(W) **(mW/(m•K))	MSI***	Number of non-reported parameters (N)	Ref.
FIXIT 222	Y	Y	N	Y	p	N	N	p	3 out of 8	[36]
FIXIT 244	Y	Y	N	Y	N	N	N	N	5 out of 8	[37]
HAGATHERM Typ Aerogel 402	Y	N	N	Y	p	P	N	N	4 out of 8	[38]
HECK AERO iP WA	P	N	N	P	P	P	N	N	4 out of 8	[39]
HECK AERO iP OWA	P	N	N	P	P	P	N	N	4 out of 8	[39]
Interbran Premium 028	P	N	N	Y	Y	P	N	N	4 out of 8	[40]
XERAL SP 028	P	N	N	Y	Y	P	N	N	4 out of 8	[41]
XERAL SP 036	P	N	N	Y	Y	P	N	N	4 out of 8	[42]
XERAL SP 055	P	N	N	Y	Y	P	N	N	4 out of 8	[43]
Poraver	Y	N	N	N	N	P	N	N	6 out of 8	[44]
Number of products not reporting data on the parameter (N)	0 out of 10	8 out of 10	10 out of 10	1 out of 10	2 out of 10	2 out of 10	10 out of 10	9 out of 10	(On average) 4 out of 8	

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

Table 13
Increase in thermal conductivity (%) of ACMs studied in [31].

Aerogel content \ Aging factor	T	Freeze-thaw	RH	UV + T + RH
0 %	5	6	22	25
25 %	3	3	16	17
60 %	4	4	12	15
70 %	1	3	10	7
80 %	1	2	8	4
90 %	0	2	6	4

The risk of exposure when working with large quantities of silica aerogels, e.g. by inhalation of the resulting dust, was also found to be low. However, inhalation of crystalline silica can cause other ailments such as respiratory diseases and silicosis [114].

Cuce et al. [15] listed possible hazardous effects on human health that may result from contact with silica aerogels. The information was based on a report prepared by the Aspen aerogels company [115]. Among various health effects, it was found that inhalation of airborne dust from aerogels may cause irritation in the upper respiratory tract. Exposure of eyes and human skin to the produced dust of aerogels could create a drying sensation and irritation. In addition, the dust could cause a scratchy throat and redness of the eyes and skin. With excessive exposure and inhalation of the dust, some pre-existing chronic lung conditions such as asthma, emphysema and bronchitis may worsen. Due to these typical health problems with aerogels, it has been recommended to avoid skin contact and inhalation by wearing protective gloves and respiratory masks [115].

In 2015, a study was published by the Cabot company [116]. In this report, it was claimed that many published articles dealing with the possible hazardous effects of aerogels did not fully distinguish between crystalline silica and synthetic amorphous silica. It was stated that these two are chemically identical but have major structural differences. Because of these structural differences, the hazardous effects on human health from them would also be different. According to this article, exposure and inhalation of the crystalline form of silica can cause severe health problems such as the disease silicosis and reduced lung function capacity. Amorphous silica, on the other hand, would be removed from the lungs via the lungs’ natural protective mechanisms, unlike crystalline silica, which remains in the lungs. Amourphous silica includes pyrogenic (fumed) silica, precipitated silica, and silica gels and aerogels. In a study presented in the same article, the health status of 165 workers exposed to synthetic amorphous silica dust over an average period of 8.6 years was observed. The analysis in this study showed that there was no correlation between lung function and exposure to synthetic

Table 14
Summary of reported accelerated aging studies on ACMs.

Material	Aging factor	Test condition	Experimental duration	Est. real lifetime	Result	Ref.
(CA-Ryerson)	T	70℃	70 days	20 years	Up to ~ 17% increment of λ	[104]
	Freeze- thaw	40℃, (−30) ℃	170 days/cycles		Up to ~ 17% increment of λ	
	RH	90%, (40℃)	82 days		–	
(CA-Ryerson)	T	70℃, (15 %)	68 days	20 years	Up to ~ 4% increment of λ	[31]
	Freeze- thaw	40℃, (−30) ℃	170 days/cycles		Up to ~ 4% increment of λ	
	RH	70%, (45℃)	104 days		~ 16% increment of λ (on average)	
	UV radiation, RH, T	-, 100%, 55℃	28 days		Up to ~ 17% increment of λ	
Quick-Mix	T- Rain	70℃, 1.5 l/m^2.min	20 days/80 cycles	–	High water uptake in the ACM system	[105,106]
	T,T	50℃, (−20) ℃	5 days/5 cycles		30–60 % reduced adhesive tensile strength, Minor chipping of surface	
	Rain,T,T, Rain	1.5 l/m^2.min, (−20)℃, 20℃, 1.5 l/m^2.min	20 days/30 cycles		Observed crack propagation (crack width < 0.15 mm)	
PT-Lisboa-37	T	23℃, (−20) ℃	30 cycles	–	Reduced mechanical strength (not adhesive strength)	[107]
	Freeze-thaw	60℃, (−15)℃			Reduced liquid water absorption	
	Water immersion	60℃, (−5) ℃				
(Trial mixture)	Freeze-thaw	60℃, (−15) ℃	20 cycles	–	~ 15 % Weight loss, Up to ~ 13% reduction of λ,	[108]
	T, RH, Radiation	60℃, (−15) ℃, 65 %	8–8 cycles		Up to ~ 2 % increased compressive strength, ~ 10 % increased Young's modulus	

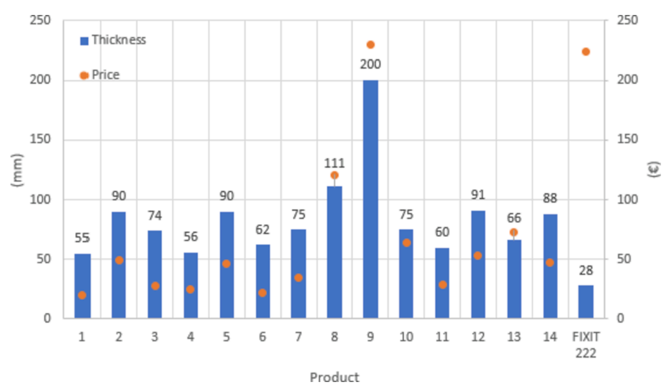

Fig. 4. The required thicknesses and prices of 14 TIPs and one ACM to obtain a thermal resistance of 1 (m2 · K)/W [87,97].

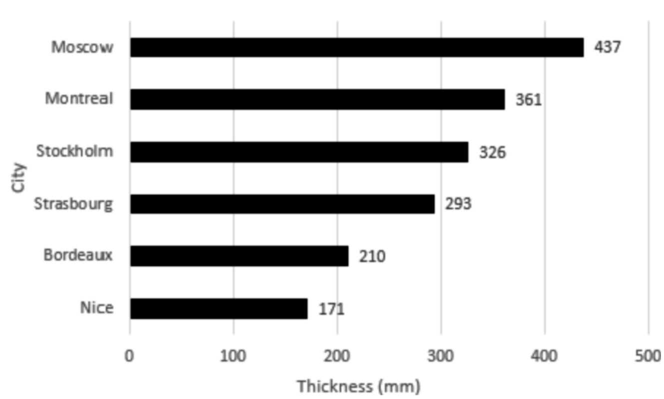

Fig. 5. The optimal thickness for FR-MINES in different cities [22].

amorphous silica dust. 143 of 163 workers were also analyzed by medical radiography. It was found that none of the 143 workers had radiographic pneumoconiosis. The respiratory symptoms in some of the workers were attributed to smoking and not exposure to the dust.

As for the silica aerogels currently used in various commercial ACM

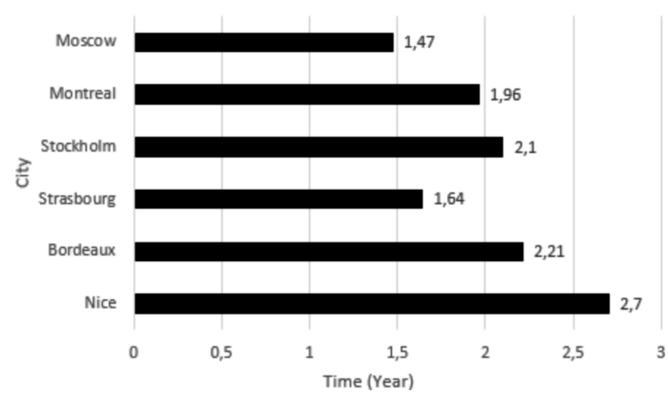

Fig. 6. The calculated payback period for FR-MINES in different cities [22].

products on the market, there are granules with particle diameters around 0.5–5 mm [17,116]. The majority of aerogel particles in ACM products are not in nano size. In [17], statements from a human-toxicological study on the ACM product FIXIT 222 were cited. In this study, it was claimed that silica aerogel and its main ingredient, amorphous silica, were considered non-toxic and without potential health risks.

According to the literature review conducted, and regarding the health concerns about ACMs, none of the manufacturers stated that the use of ACMs was associated with major uncertainties for the user. However, there were recommendations such as wearing protective gloves and respiratory masks. No previous cases of health hazards on humans from the use of ACMs were identified.

3. Full-scale performance evaluation of ACMs

Since the early development of ACMs in 2012, there are several buildings in European countries where ACMs have been used. Most of these buildings are located in Switzerland, where the first ACM product was developed and commercialized. According to [117], about 70 buildings were retrofitted with ACMs in Switzerland between the years 2012 and 2014. Lately, this number has increased to more than 200 buildings [45].

Table 15
List of full-scale studies on ACMs 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 FR-MINES 25 cm Concrete 16 cm Glass wool 1.3 cm Plaster	The evaluation of the studied wall configurations was partly 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.	[21]
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 FR-MINES 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, ACM performed better than other insulation materials.	[23]
Nice- France	Thickness optimization and cost analysis of ACM for different climates.	–	4 cm FR-MINES 42 cm of brick monomur	The analyses were performed partly 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.	[22]
Le Bourget-du-Lac- France	Hygrothermal performance evaluation of façades covered with ACM. Comparison of the theoretical and the in-situ measured U-value.	Brick Plasterboard	ACM (unspecified) 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.	[120]
Vienna- Austria	Evaluation of the long-term performance of ACM.	20 mm lime-cement rendering 250 mm hollow bricks 15 mm gypsum plaster	4 cm FIXIT 222 with different finishing layers 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. A reduction of the temperature difference between the indoor air and the surfaces was measured up to 4 ℃. No visible cracking.	[32]
Vienna- Austria	Evaluation of the long-term performance of ACM (3 years).	20 mm lime-cement rendering 250 mm hollow bricks 15 mm gypsum plaster	4 cm FIXIT 222 with different finishing layers (+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.	[98]
Vienna- Austria	Evaluation of thermal performance and workability of ACM without reinforcement mesh	Not specified	Not specified (ACM applied externally)	A reduction of external surface temperature by 2–2.5 ℃ (one-time infrared thermography), compared to the original façade.	[121]
Röthis- Austria	Evaluation of external surface condition on samples of ACM-system without reinforcement mesh, exposed to weathering	Brick	Several final render and mineral paint 6 cm of ACM Brick	Small cracks on finishing surface of some samples after three winter seasons Color change and frost-induced ablations on finishing surface of some samples An accepted overall performance of the ACM system without reinforcement (according to the authors of [121])	[121]

(continued on next page)

Table 15 (*continued*)

Location	Aim of the study	Construction before (From exterior)	Construction after (From exterior)	Result	Ref.
Sissach-Switzerland	Retrofit of an inhabited 14th century mill by ACM. Assessment of energy performance of ACM, 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 FIXIT 222 + 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 Zürich, 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.	[17]
Dällikon-Switzerland	Application of six different ACMs (four unspecified and two from Quick-Mix) to the south-orientated exterior wall of an office building. Evaluation of the thermal performance and drying behavior of the ACMs.	Prefabricated concrete	Final coating 2 layers of supporting plaster Reinforcement mesh 2 layers of ACMs Primer and roughcast Prefabricated concrete	Ongoing measurements: energy evaluations were not performed and therefore not reported. After four months of data collection, the layer with Quick-Mix was still damp.	[105]
Berlin- Germany	Retrofit of a 30 m high precast concrete building with ACM. Evaluation of the energy performance of ACM, 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 ACM + 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.	[18]
Turin- Italy	Evaluation of energy performance of ACM: heat losses and thermal bridges. Evaluation of potential risks for condensation on the internal wall surfaces with and without ACM.	Plaster Brick-air cavity-Brick Plaster	Plaster Brick-air cavity- Brick Plaster Primer 1.2–1.5 cm of IT-Torino	27% reduction in thermal transmittance. 1.5°C higher internal surface temperature. Reduced influence of thermal bridges. 2 months were required to remove the water initially in the mixture. No interior surface condensation at 60% internal RH- levels.	[16,26]
Turin-Italy	Evaluation of thermal performance of ACM under operating conditions.	52 cm brick	52 cm brick 4.5 cm Vimark	60 % Reduction in heat transfer coefficient. 21%[12]/ 17%[122] higher measured thermal conductivity of the ACM than the declared value based on laboratory measurements, due to higher moisture content (ongoing measurements).	[12,122]
Oslo- Norway	Evaluation of thermal performance of ACM in the Norwegian climate.	Plaster Brick Plaster	Lime-based paint 7 mm: FIXIT 223 (reinforcement mortar) + reinforcement mesh + FIXIT 493 (surface stabilizer) 7 cm FIXIT 222 FIXIT 670 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.	[33]

In this section, scientific and published articles reporting full-scale studies on ACMs are reviewed. A list of these studies and the general details and results are summarized in Table 15. In Table 16, the reviewed full-scale studies on ACMs are quantitively analyzed with respect to several performance criteria. The included studies are full-scale tests conducted in France, Austria, Switzerland, Germany, Italy and Norway. The selected ACMs in all studied concerned were either trial-mixtures or one specific commercial product. However, Ganobjak et al. [45] reported a project in Switzerland using a different commercially available ACM product. This project involved the renovation of a building from 1554, Manoir de Cormondrèche, where 2 cm of ACM was applied to the exterior façades. The U-value was reduced from 1.4 W/(m^2 • K) to 0.4 W/(m^2 • K) [118,119].

In the review conducted, 14 full-scale studies on ACMs were identified. The full-scale studies involved renovations at various scales. In some studies, ACMs were applied to individual façade elements and in some cases to all façade surfaces. All investigated objects were buildings with uninsulated building envelopes. As illustrated in Table 16, in 11 out of 14 cases, the façade was either brick or concrete. In 7 out of 14 studies, only 5 cm or less of ACM was applied. In most studies, 12 out of 14, ACM was applied externally. The primary focus of most of these studies was the thermal performance of ACMs. 9 studies explicitly indicated an improved thermal performance with the addition of ACM. In the cases studied, the addition of 1.5–6 cm of ACM 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 14 studies. Apart from evaluating the thermal performance, it was claimed in 3 out of 14 studies that along with the addition of ACMs, 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 ACMs were identified. Minor damage in the form of visible cracks was reported twice.

The Application of ACMs to surfaces was done manually or with the

Table 16
Summary of reviewed full-scale studies on ACMs 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	[21]Nice	[23]Nice	[22]Nice	[120]Le Bourget -du-Lac	[32] Vienna	[98] Vienna	[121] Vienna	[121] Vienna	[17] Sissach	[105] Dällikon	[18] Berlin	[16,26] Turin	[12] Turin	[33] Oslo	Number of fulfilled criterion (Y)
Type of ACM	FR_MINES	FR_MINES	FR_MINES	NS	FIXIT 222	FIXIT 222	FIXIT 222	FIXIT 222	FIXIT 222	Quick-Mix	FIXIT 222	IT-Torino	Vimark	FIXIT 222	–
Building type: façade material	Concrete	Concrete	–	Brick	Brick	Brick	–	Brick	Limestone	Concrete	Concrete	Brick	Brick	Brick	–
External/internal application of ACM	EXT	EXT	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	NS	NS	N	N	Y	1 out of 14
ACM thickness less than 5 cm	Y	Y	Y	NS	Y	Y	NS	N	N	NS	N	Y	Y	N	7 out of 14
Reported improved thermal performance	Y	Y	P	P	N	Y	Y	N	Y	NS	Y	Y	Y	Y	9 out of 14
Reported reduced U-value of façade by more than 50 %	N	N	N	N	N	Y	NS	N	Y	NS	Y	N	Y	N	4 out of 14
Reported improved thermal comfort	N	N	N	N	Y	N	NS	N	Y	N	N	Y	N	N	3 out of 14
Reported major damages	N	N	N	N	N	N	N	N	N	N	N	N	N	N	0 out of 14
Reported minor damages	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N	2 out of 14
Reported visible cracks	N	N	N	N	N	Y/N	N	Y	N	N	N	N	N	N	1 (2) out of 14
Reported usage of reinforcement mesh	N	N	N	N	N	N/Y	N	N	Y	Y	Y	N	N	N	3 (4) out of 14
Reported reduced risk for moisture damage	Y	N	N	N	N	N	N	N	Y	N	N	P	N	Y	3 out of 14

help of spray machines. However, most studies did not explicitly describe the chosen application method. The application of ACMs to façades was supplemented by additional layers of mortars to increase the adhesive to the underlying surface and to protect the ACM. 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 ACMs in multilayer wall system were not explicitly described in the studies reviewed. However, ACM manufacturers presented recommendations on what other materials should be used along with their respective ACM and for different types of construction. The background to how these recommendations were developed was generally not described. Finally, no study reported major problems regarding the compatibility of ACMs with the selected adjacent materials.

3.1. Performance evaluation by means of laboratory pilot studies and simulations

Apart from the full-scale studies presented previously in this chapter, hygrothermal simulations and pilot studies on laboratory scale have also been used to evaluate the performance of ACMs. In Table 17 the main outcomes of these studies are presented. In many of the previously presented articles on full-scale studies, results from some simulation case studies were presented. These articles are specified in Table 15. The studies listed in Table 17 are based solely on hygrothermal simulation or laboratory-based case studies. Majority of the studies presented in Table 17, evaluated the performance of AMCs applied internally. The results showed that the material performed well in most of cases when applied internally. Due to its high vapor diffusivity, the drying towards interior was not negatively affected. However, several studies highlighted the importance of the material properties of the exterior finishing on the hygrothermal performance of the wall and the ACM. Too high water intrusion in the wall could increase the moisture risks such as moisture accumulation and condensation risks.

As illustrated in this chapter, the full-scale studies evaluating the hygrothermal performance of ACMs are significant but, in most cases, mainly of local value. The studies are conducted in limited numbers of countries and climate conditions. Despite the limited number of simulation and laboratory-based case studies, mainly internal application of ACMs, the conducted studies have highlighted the importance of correct choice of materials combined with ACMs. More studies are needed for the external application of ACMs as well. A more-in depth knowledge about the AMCs and the corresponding multilayer wall system, in case of damage and when exposed to more severe climate conditions is required. Another important point is the required drying time of the material before the declared thermal conductivities can be achieved. Several studies have indicated a required drying time between 2 and 12 months. The rather large variation in terms of initial drying time may be due to the fact that these studies were conducted in different climates and with different ACMs.

4. Conclusions

This article presented a literature review of aerogel-based coating mortars, both laboratory-based trial mixtures and commercial ones. The aim of the study was to collect and systematize the available information on contemporary aerogel-based coating mortars, focusing on their hygrothermal, mechanical and long-term performance. The review article considered studies on material level, full-scale studies, laboratory-based pilot studies and hygrothermal simulation case studies. Based on the conducted review, the knowledge gaps and missing data necessary to conduct moisture risk analyses and the need for further research were highlighted.

When aiming for energy-savings, it is evident that aerogel-based

Table 17
List of studies on ACMs by means of hygrothermal simulations and laboratory-based pilot testing reported in scientific articles.

Type of study	Aim of the study	Internal/ external Application of ACM	Result	Ref.
Simulation	Evaluation of hygrothermal performance of internal insulations including ACM in different wall configurations and exterior finishing	Internal	The capillary suction properties of the final exterior coating have high impact on the moisture accumulation in the construction and ACM on the inside. ACM, due to its high vapor diffusivity, does not slow down the drying rate towards interior.	[123]
Simulation Laboratory testing	Evaluation of hygrothermal performance of internal insulations including ACM in different wall configurations and exterior finishing	Internal	The internal Application of ACM can introduce a valid solution for walls with vapor-tight exterior finishing. Internal Application of ACM can in most cases be considered as a moisture safe solution for retrofitting of historical walls. However, each case needs to be investigated separately.	[124]
Laboratory testing	Evaluation of hygrothermal performance of a masonry wall insulated internally by ACM and exposed to wetting conditions	Internal	The conclusion of the paper is focused on the performance of the developed test set-up and validation of the testing methods. No explicit conclusions on the internal Application of ACM.	[19,125]
Simulation	Evaluation of hygrothermal performance of masonry walls with different exterior finishing. Risk evaluation of biological deterioration for wooden structures in the studied walls renovated by internal	Internal	The vapor diffusivity and liquid transport properties of the exterior coating have higher impact on the hygrothermal performance of the walls and the corresponding risk for biological deterioration of	[126]

(*continued on next page*)

Table 17 (*continued*)

Type of study	Aim of the study	Internal/ external Application of ACM	Result	Ref.
	insulation including ACM		wooden-based elements, compared to the type of internal insulation.	
Simulation	Evaluation of hygrothermal performance and occurrence of freeze-thawing and icing in masonry walls insulated internally by among others ACM.	Internal	The addition of ACM on the interior, increases the number of freeze-thawing and ice content in the masonry wall. The risks are more significant for regions with wet and moderate climate compared to cold climate regions.	[127]
Simulation	Evaluation of hygrothermal performance of walls insulated internally by among others ACM, with different exterior finishing.	Internal	The moisture performance and capillary properties of the exterior finishing is identified as the parameter affecting the hygrothermal performance of the interior insulation as most.	[128]
Simulation	Evaluation of risk of condensation in middle of brick walls insulated by ACM considering the position and thickness of ACM	Both	Internal insulation by ACM can increase the condensation risk. The thickness of ACM has less impact on the risk for condensation, compared to its position in the wall.	[129]
Simulation	Evaluation of hygrothermal performance of light-weight concrete wall insulated by ACM, located in different climates	External	Increased risk for external condensation for locations at higher latitude The property of the external finishing is important to reduce/prevent the rainwater intrusion and to control the water content in the ACM system.	[6]

coating are promising materials to increase energy efficiency in buildings and potentially create slimmer building envelopes. Material properties such as temperature and moisture dependent thermal conductivity, heat capacity, flexural and adhesive strength and moisture sorption isotherms are not readily available for most contemporary aerogel-based mortars. For properties on the long-term durability, research has so far been limited to five studies addressing accelerated aging tests and natural exposure studies. It is therefore difficult to make a general concluding statement on the long-term performance of aerogel-based plasters. However, the studies presented, suggest that the aging of aerogel-based plasters are not leading to significantly changed properties. The hygrothermal and mechanical compatibility of aerogel-based mortars with adjacent materials in multilayer wall systems has not been fully investigated in previous research. To the best of the authors' knowledge, there are no scientific guidelines to evaluate and ensure the compatibility of aerogel-based mortars with other building materials in various wall types and climates. However, there are suggestions from some producers on the selection of adjacent complementary materials. Based on the full-scale studies conducted to date, no major issues have been identified regarding the compatibility of aerogel-based mortars with the selected supplementary materials. Regarding the studies focusing on the hygrothermal performance of aerogel-based coating mortars, the full-scale studies are significant but mainly of local value. The hygrothermal performance of ACMs, applied externally and exposed to severe outdoor conditions need to be further studied. Also, the knowledge on the moisture drying performance of ACMs, at early-stage and before the declared thermal conductivities can be achieved needs to increase.

Future research in the field of aerogel-based coating mortars could be related to the evaluation of hygrothermal and mechanical properties, as well as long-term durability of the materials, to obtain a complete and reliable dataset necessary for risk assessment analyses. In addition, the compatibility of aerogel-based mortars with other new and existing materials in different multilayer wall systems and climatic conditions need to be further evaluated. The hygrothermal performance of aerogel-based coating mortars at early-stage of application and when exposed to severe conditions should also be considered in future works.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors would like to gratefully acknowledge the Swedish Energy Agency (46822-1) for financial support.

References

[1] M. Koebel, A. Rigacci, P. Achard, Aerogel-based thermal superinsulation: an overview, J. Sol-Gel Sci. Technol. 63 (3) (2012) 315–339, https://doi.org/10.1007/s10971-012-2792-9.
[2] H. Maleki, Recent advances in aerogels for environmental remediation applications: A review, Chem. Eng. J. 300 (2016) 98–118, https://doi.org/10.1016/J.CEJ.2016.04.098.
[3] E. Cuce, P.M. Cuce, C.J. Wood, S.B. Riffat, Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings, Energy Build. 77 (2014) 28–39, https://doi.org/10.1016/J.ENBUILD.2014.03.034.
[4] R. Baetens, B.P. Jelle, A. Gustavsen, Aerogel insulation for building applications: A state-of-the-art review, Energy Build. 43 (4) (2011) 761–769, https://doi.org/10.1016/j.enbuild.2010.12.012.
[5] T. Stahl, S. Brunner, M. Zimmermann, W.K. Ghazi, Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications, Energy Build. 44 (2012) 114–117, https://doi.org/10.1016/J.ENBUILD.2011.09.041.
[6] J. Maia, M. Pedroso, N.M.M. Ramos, P.F. Pereira, I. Flores-Colen, M.G. Gomes, L. Silva, Hygrothermal performance of a new thermal aerogel-based render under distinct climatic conditions, Energy Build. 243 (2021) 111001, https://doi.org/10.1016/j.enbuild.2021.111001.
[7] S. Fantucci, E. Fenoglio, V. Serra, M. Perino, M. Dutto, V. Marino, Hygrothermal Characterization of High-Performance Aerogel-Based Internal Plaster, Smart Innov. Syst. Technol., Springer (2020) 259–268, https://doi.org/10.1007/978-981-32-9868-2.

[8] E. Lucchi, F. Roberti, T. Alexandra, Definition of an experimental procedure with the hot box method for the thermal performance evaluation of inhomogeneous walls, Energy Build. 179 (2018) 99–111, https://doi.org/10.1016/J.ENBUILD.2018.08.049.
[9] E. Lucchi, F. Becherini, M.C. Di Tuccio, A. Troi, J. Frick, F. Roberti, C. Hermann, I. Fairnington, G. Mezzasalma, L. Pockelé, A. Bernardi, Thermal performance evaluation and comfort assessment of advanced aerogel as blown-in insulation for historic buildings, Build. Environ. 122 (2017) 258–268, https://doi.org/10.1016/j.buildenv.2017.06.019.
[10] European Commission. Energy performance of buildings directive 2019. https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed December 10, 2020).
[11] International Energy Agency. Buildings A source of enormous untapped efficiency potential 2020. https://www.iea.org/topics/buildings (accessed August 12, 2020).
[12] E. Fenoglio, S. Fantucci, M. Perino, V. Serra, M. Dutto, V. Marino, Energy retrofit of residential buildings with a novel super-insulating aerogel-based plaster, AiCARR J 61 (2020) 44–48.
[13] A. Soares, J.M. de Fátima, I. Flores-Colen, L.M. Ilharco, J. de Brito, EN 998–1 performance requirements for thermal aerogel-based renders, Constr. Build. Mater. 179 (2018) 453–460, https://doi.org/10.1016/J.CONBUILDMAT.2018.05.197.
[14] M. Pedroso, I. Flores-Colen, J.D. Silvestre, M.G. Gomes, L. Silva, L. Ilharco, Physical, mechanical, and microstructural characterisation of an innovative thermal insulating render incorporating silica aerogel. Energy Build 2020;211: 109793. https://doi.org/10.1016/J.ENBUILD.2020.109793.
[15] E. Cuce, P.M. Cuce, C.J. Wood, S.B. Riffat, Toward aerogel based thermal superinsulation in buildings: A comprehensive review, Renew. Sustain. Energy Rev. 34 (2014) 273–299, https://doi.org/10.1016/J.RSER.2014.03.017.
[16] S. Fantucci, E. Fenoglio, G. Grosso, V. Serra, M. Perino, V. Marino, M. Dutto, Development of an aerogel-based thermal coating for the energy retrofit and the prevention of condensation risk in existing buildings, Sci. Technol. Built. Environ. 25 (9) (2019) 1178–1186, https://doi.org/10.1080/23744731.2019.1634931.
[17] T. Stahl, K. Ghazi Wakili, S. Hartmeier, E. Franov, W. Niederberger, M. Zimmermann, Temperature and moisture evolution beneath an aerogel based rendering applied to a historic building, J. Build. Eng. 12 (2017) 140–146, https://doi.org/10.1016/J.JOBE.2017.05.016.
[18] K. Ghazi Wakili, C. Dworatzyk, M. Sanner, A. Sengespeick, M. Paronen, T. Stahl, Energy efficient retrofit of a prefabricated concrete panel building (Plattenbau) in Berlin by applying an aerogel based rendering to its façades, Energy Build. 165 (2018) 293–300, https://doi.org/10.1016/J.ENBUILD.2018.01.050.
[19] M. Guizzardi, D. Derome, R. Vonbank, J. Carmeliet, Hygrothermal behavior of a massive wall with interior insulation during wetting, Build. Environ. 89 (2015) 59–71, https://doi.org/10.1016/J.BUILDENV.2015.01.034.
[20] WALL-ACE 2016. https://www.wall-ace.eu/ (accessed November 27, 2020).
[21] M. Ibrahim, E. Wurtz, P.H. Biwole, P. Achard, H. Sallee, Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering, Energy Build. 84 (2014) 241–251, https://doi.org/10.1016/J.ENBUILD.2014.07.039.
[22] M. Ibrahim, P.H. Biwole, P. Achard, E. Wurtz, G. Ansart, Building envelope with a new aerogel-based insulating rendering: Experimental and numerical study, cost analysis, and thickness optimization, Appl. Energy 159 (2015) 490–501, https://doi.org/10.1016/J.APENERGY.2015.08.090.
[23] M. Ibrahim, P.H. Biwole, E. Wurtz, P. Achard, A study on the thermal performance of exterior walls covered with a recently patented silica-aerogel-based insulating coating, Build. Environ. 81 (2014) 112–122, https://doi.org/10.1016/J.BUILDENV.2014.06.017.
[24] M. Ibrahim, E. Wurtz, P. Achard, P. Henry Biwole, P.H. Biwole, Fostering energy efficiency in buildings through aerogel-based renders. 2015.
[25] S. Fantucci, E. Fenoglio, F. Isaia, V. Serra, M. Perino, M. Dutto, et al. Development of aerogel based internal thermal plasters for the energy retrofit of existing buildings: First results, 2019, 557-562.
[26] S. Fantucci, E. Fenoglio, G. Grosso, V. Serra, M. Perino, M. Dutto, et al. Retrofit of the existing buildings using a novel developed aerogel-based coating: results from an in-field monitoring. 7th Int. Build. Phys. Conf. IBPC2018, Syracuse University Libraries; 2018, p. 283–8. https://doi.org/10.14305/ibpc.2018.be-7.06.
[27] C. Buratti, E. Moretti, E. Belloni, F. Agosti, C. Buratti, E. Moretti, et al., Development of Innovative Aerogel Based Plasters: Preliminary Thermal and Acoustic Performance Evaluation, Sustainability 6 (2014) 5839–5852, https://doi.org/10.3390/su6095839.
[28] J.M. de Fátima, A. Soares, L.M. Ilharco, I. Flores-Colen, J. de Brito, Aerogel-based renders with lightweight aggregates: Correlation between molecular/pore structure and performance, Constr. Build. Mater. 124 (2016) 485–495, https://doi.org/10.1016/J.CONBUILDMAT.2016.07.103.
[29] M.d.F. Júlio, A. Soares, L.M. Ilharco, I. Flores-Colen, J. de Brito, Silica-based aerogels as aggregates for cement-based thermal renders, Cem. Concr. Compos. 72 (2016) 309–318, https://doi.org/10.1016/j.cemconcomp.2016.06.013.
[30] R.H. Nosrati, U. Berardi, Hygrothermal characteristics of aerogel-enhanced insulating materials under different humidity and temperature conditions, Energy Build. 158 (2018) 698–711, https://doi.org/10.1016/J.ENBUILD.2017.09.079.
[31] U. Berardi, R.H. Nosrati, Long-term thermal conductivity of aerogel-enhanced insulating materials under different laboratory aging conditions, Energy 147 (2018) 1188–1202, https://doi.org/10.1016/j.energy.2018.01.053.
[32] K.G. Wakili, T.h. Stahl, E. Heiduk, M. Schuss, R. Vonbank, U. Pont, C. Sustr, D. Wolosiuk, A. Mahdavi, High performance aerogel containing plaster for historic buildings with structured façades, Energy Procedia 78 (2015) 949–954, https://doi.org/10.1016/j.egypro.2015.11.027.
[33] C. Solheim, Application of Aerogel-based plaster for refurbishment and preservation of a listed historic masonry building in Norway-an in-situ energy efficiency study 2018.
[34] M. Pedroso, I. Flores-Colen, J.D. Silvestre, M.d.G. Gomes, Nanomaterials' Influence on the Performance of Thermal Insulating Mortars—A Statistical Analysis. Appl Sci 2020 10 (7) (2020) 2219, https://doi.org/10.3390/app10072219.
[35] A.N. Karim, P. Johansson, A.S. Kalagasidis, Super insulation plasters in renovation of buildings in Sweden: energy efficiency and possibilities with new building materials, IOP Conf Ser Earth Environ Sci 588 (2020), 042050, https://doi.org/10.1088/1755-1315/588/4/042050.
[36] Fixit. Fixit 222 Aerogel Hochleistungsdämmputz 2020. https://www.fixit.ch/Home/Produkte/Restaurierungs-und-Sanierungsprodukte/Aerogel-Daemmputze/Fixit-222-Aerogel-Hochleistungsdaemmputz (accessed April 23, 2020).
[37] RÖFIX. FIXIT 244 2020. https://www.roefix.at/media/importer_assets/211827.pdf (accessed August 12, 2020).
[38] HAGA AG Naturbaustoffe. HAGATHERM Wärmedämmputz Typ Aerogel 2018. https://www.haganatur.ch/portfolio_page/hagatherm-waermedaemmputz-typ-aerogel/ (accessed August 18, 2020).
[39] Wall-system. HECK AERO 2020. https://www.wall-systems.com/de/download (accessed August 18, 2020).
[40] Interbran Baustoff. Interbran Premium 028 2017. https://www.agitec.ch/page/PDF-Dateien/Technische-Merkblaetter/Deutsch/TDB_Interbran_Premium_Daemmputz_028.pdf?m=1527205755& (accessed August 12, 2020).
[41] Interbran Baustoff GmbH. XERAL SP 028 Thermal insulating plaster TECHNICAL PRODUCT DATA SHEET 2020. https://www.xeral.com/Produktdatenblatt_en/DS_XERAL_SP_028_Thermal_insulating_plaster.pdf (accessed January 13, 2021).
[42] Interbran Baustoff GmbH. XERAL SP 036 Thermal insulating plaster TECHNICAL PRODUCT DATA SHEET 2020. https://www.xeral.com/Produktdatenblatt_en/DS_XERAL_SP_036_Thermal_insulating_plaster.pdf (accessed January 13, 2021).
[43] Interbran Baustoff GmbH. XERAL SP 055 Thermal insulating plaster TECHNICAL PRODUCT DATA SHEET 2020. https://www.xeral.com/Produktdatenblatt_en/DS_XERAL_SP_055_Thermal_insulating_plaster.pdf (accessed January 13, 2021).
[44] Poraver. Poraver 2020. https://www.poraver.com/en/aerogel_thermal_insulating_render/ (accessed August 12, 2020).
[45] M. Ganobjak, S. Brunner, J. Wernery, Aerogel materials for heritage buildings: Materials, properties and case studies, J Cult Herit 42 (2020) 81–98, https://doi.org/10.1016/j.culher.2019.09.007.
[46] D. Del Curto, V. Cinieri, Aerogel-Based Plasters and Energy Efficiency of Historic Buildings Literature Review and Guidelines for Manufacturing Specimens Destined for Thermal Tests. Sustainability 12 (22) (2020) 9457, https://doi.org/10.3390/su12229457.
[47] A. Lamy-Mendes, A.D.R. Pontinha, P. Alves, P. Santos, L. Durães, Progress in silica aerogel-containing materials for buildings' thermal insulation, Constr. Build. Mater. 286 (2021) 122815, https://doi.org/10.1016/j.conbuildmat.2021.122815.
[48] S.K. Adhikary, D.K. Ashish, Žymantas Rudžionis, Aerogel based thermal insulating cementitious composites: A review, Energy Build. 245 (2021) 111058, https://doi.org/10.1016/j.enbuild.2021.111058.
[49] S. Ng, B.P. Jelle, Y. Zhen, Ó.H. Wallevik, Effect of storage and curing conditions at elevated temperatures on aerogel-incorporated mortar samples based on UHPC recipe, Constr. Build. Mater. 106 (2016) 640–649, https://doi.org/10.1016/j.conbuildmat.2015.12.162.
[50] S. Ng, B.P. Jelle, T. Stæhli, Calcined clays as binder for thermal insulating and structural aerogel incorporated mortar, Cem. Concr. Compos. 72 (2016) 213–221, https://doi.org/10.1016/j.cemconcomp.2016.06.007.
[51] A. Berge, P. Johansson, Literature Review of High Performance Thermal Insulation, 2012.
[52] U. Heinemann, EBC Annex 65- Report of Subtask I: State of the Art and Case Studies 2020. https://vipa-international.org/uploads/kcFinder/files/EBC Annex 65-Report-subtask-I-SoA-2020-01-03-v0%281%29.pdf.
[53] N. Gaponik, A.-K. Herrmann, A. Eychmüller, Colloidal nanocrystal-based gels and aerogels: Material aspects and application perspectives, J. Phys. Chem. Lett. 3 (1) (2012) 8–17, https://doi.org/10.1021/jz201357r.
[54] A. Soleimani Dorcheh, M.H. Abbasi, Silica aerogel; synthesis, properties and characterization, J. Mater. Process. Technol. 199 (1-3) (2008) 10–26, https://doi.org/10.1016/j.jmatprotec.2007.10.060.
[55] F. Schüth, K.S.W. Sing, J. Weitkamp, Handbook of Porous, Media. (2002), https://doi.org/10.1201/b18614.
[56] S.B. Riffat, G. Qiu, A review of state-of-the-art aerogel applications in buildings, Int J Low-Carbon Technol 8 (1) (2013) 1–6, https://doi.org/10.1093/ijlct/cts001.
[57] H. Maleki, L. Durães, C.A. García-González, P. del Gaudio, A. Portugal, M. Mahmoudi, Synthesis and biomedical applications of aerogels: Possibilities and challenges, Adv. Colloid Interface Sci. 236 (2016) 1–27, https://doi.org/10.1016/J.CIS.2016.05.011.
[58] European Committee for Standardization (CEN). EN 998-1 Specification for mortar for masonry – Part 1: Rendering and plastering mortar. 2016.
[59] A.N. Karim, Aerogel-based plasters for renovation of buildings in Sweden: Identification of possibilities, information deficiencies and challenges, Licenciate thesis, Chalmers University of Technology, 2021.

[60] European Committee for Standardization (CEN). EN 1015-1 Methods of test for mortar for masonry – Part 1: Determination of particle size distribution (by sieve analysis). 1998.
[61] European Committee for Standardization (CEN). EN 1015-2 Methods of test for mortar for masonry – Part 2: Bulk sampling of mortars and preparation of test mortars 1998.
[62] European Committee for Standardization (CEN). EN 1015-17 Methods of test mortar for masonry – Part 17 : Determination of water-soluble chloride content Murbruk. 2000.
[63] European Committee for Standardization (CEN). EN 1015-18 Methods of test for mortar for masonry – Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar. 2002.
[64] European Committee for Standardization (CEN). EN 1015-19 Methods of tests for mortar for masonry – Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars. 1998.
[65] European Committee for Standardization (CEN). EN 1015-21 Methods of test for mortar for masonry – Part 21: Determination of the compatibility of one-coat rendering mortars with substrates. 2002.
[66] European Committee for Standardization (CEN). EN 1745 Masonry and masonry products – Methods for determining thermal properties, 2012.
[67] European Committee for Standardization (CEN). EN 13501-1 Fire classification of construction products and building elements – Part 1: Classification using data from reaction to fire tests. 2019.
[68] European Committee for Standardization (CEN). EN 1015-3 Methods of test for mortar for masonry – Part 3: Determination of consistence of fresh mortar (by flow table) 1999.
[69] European Committee for Standardization (CEN). EN 1015-4 Methods of test for mortar for masonry – Part 4: Determination of consistence of fresh mortar (by plunger penetration) 1998.
[70] European Committee for Standardization (CEN). EN 1015-6 Methods of test for mortar for masonry – Part 6: Determination of bulk density of fresh mortar 1998.
[71] European Committee for Standardization (CEN). EN 1015-7 Methods of test for mortar for masonry – Part 7: Determination of air content of fresh mortar 1998.
[72] European Committee for Standardization (CEN). EN 1015-9 Methods of test for mortar for masonry – Part 9: Determination of workable life and correction time of fresh mortar. 1999.
[73] European Committee for Standardization (CEN). EN 1015-10 Methods of test for mortar for masonry – Part 10: Determination of dry bulk density of hardened mortar. 1999.
[74] European Committee for Standardization (CEN). EN 1015-11 Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar. 1999.
[75] European Committee for Standardization (CEN). EN 1015-12 Methods of test for mortar for masonry – Part 12: Determination of adhesive strength of hardened rendering and plastering mortars on substrates. 2016.
[76] EN 12667:2001. Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance. 2001.
[77] W. Yang, J. Liu, Y. Wang, S. Gao, Experimental study on the thermal conductivity of aerogel-enhanced insulating materials under various hygrothermal environments, Energy Build. 206 (2020) 109583, https://doi.org/10.1016/j.enbuild.2019.109583.
[78] ASTM C518 - 10. Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. 2010.
[79] ISO 8301:1991. Thermal insulation - Determination of steady-state thermal resistance and related properties - Heat flow meter apparatus. 1991.
[80] U. Berardi, Aerogel-enhanced systems for building energy retrofits: Insights from a case study, Energy Build. 159 (2018) 370–381, https://doi.org/10.1016/J.ENBUILD.2017.10.092.
[81] P. Westgate, K. Paine, R.J. Ball, Physical and mechanical properties of plasters incorporating aerogel granules and polypropylene monofilament fibres, Constr. Build. Mater. 158 (2018) 472–480, https://doi.org/10.1016/J.CONBUILDMAT.2017.09.177.
[82] ASTM D5930 - 09. Standard Test Method for Thermal Conductivity of Plastics by Means of a Transient Line-Source Technique. 2009.
[83] M.G. Gomes, I. Flores-Colen, L.M. Manga, A. Soares, J. de Brito, The influence of moisture content on the thermal conductivity of external thermal mortars, Constr. Build. Mater. 135 (2017) 279–286, https://doi.org/10.1016/J.CONBUILDMAT.2016.12.166.
[84] EN 1159-3:2003. Advanced technical ceramics. Ceramic composites, thermophysical properties. Determination of specific heat capacity. 2003.
[85] Tleoubaev A, Brzezinski A. Thermal Diffusivity and Volumetric Specific Heat Measurements Using Heat Flow Meter Instruments Heat Flow Meter instruments' capabilities expansion View project, 2007.
[86] EN 1602:2013. Thermal insulating products for building applications – Determination of the apparent density 2013.
[87] EN ISO 8130-2:2010. Coating powders – Part 2: Determination of density by gas comparison pyknometer. 2010.
[88] European Committee for Standardization (CEN). EN ISO 12571 Hygrothermal performance of building materials and products – Determination of hygroscopic sorption properties. 2013.
[89] EN 12086:2013. Thermal insulating products for building applications – Determination of water vapour transmission properties. 2013.
[90] European Committee for Standardization (CEN). EN ISO 12572 Hygrothermal performance of building materials and products – Determination of water vapour transmission properties – Cup method. 2016.
[91] ASTM E96/E96M-16. Standard Test Methods for Water Vapor Transmission of Materials, 2016.
[92] EN ISO 10534-2:1998. Acoustics - Determination of sound absorption coefficient andimpedance in impedances tubes - Part 2: Transfer-functionmethod, 1998.
[93] C. Buratti, F. Merli, E. Moretti, Aerogel-based materials for building applications: Influence of granule size on thermal and acoustic performance, Energy Build. 152 (2017) 472–482, https://doi.org/10.1016/J.ENBUILD.2017.07.071.
[94] ASTM E1876 - 01:2006. Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration, 2006.
[95] I. Flores-Colen, M. Pedroso, A. Soares, M. Gomes, G. da, N.M.M.R. Ramos, J. Maia, et al. In-Situ Tests on Silica Aerogel-Based Rendering Walls. XV Int. Conf. Durab. Build. Mater. Components, Barcelona, 2020.
[96] S. Ximenes, A. Silva, A. Soares, I. Flores-Colen, J. de Brito, Parametric Analysis to Study the Influence of Aerogel-Based Renders' Components on Thermal and Mechanical Performance, Materials (Basel) 9 (2016) 336–1255, https://doi.org/10.3390/ma9050336.
[97] M. Pedroso, I. Flores-Colen, J.D. Silvestre, M.G. Gomes, L. Silva, P. Sequeira, J. de Brito, Characterisation of a multilayer external wall thermal insulation system. Application in a Mediterranean climate, J. Build. Eng. 30 (2020) 101265, https://doi.org/10.1016/j.jobe.2020.101265.
[98] M. Schuss, U. Pont, A. Mahdavi, Long-term experimental performance evaluation of aerogel insulation plaster, Energy Procedia 132 (2017) 508–513, https://doi.org/10.1016/J.EGYPRO.2017.09.696.
[99] M. Ibrahim, L. Bianco, O. Ibrahim, E. Wurtz, Low-emissivity coating coupled with aerogel-based plaster for walls' internal surface application in buildings: Energy saving potential based on thermal comfort assessment, J. Build. Eng. 18 (2018) 454–466, https://doi.org/10.1016/j.jobe.2018.04.008.
[100] C. Buratti, E. Moretti, E. Belloni, Aerogel Plasters for Building Energy Efficiency. Nano Biotech Based Mater. Energy Build. Effic., Cham: Springer International Publishing; 2016, p. 17–40. https://doi.org/10.1007/978-3-319-27505-5_2.
[101] A.N. Karim, P. Johansson, A.S. Kalagasidis, Long-term Performance of Silica Aerogel and Aerogel Based Composites: A Literature Review Highlighting Pathways for Further Studies, Proc. 14th Int. Vac. Insul. Symp. (2019) 87–90.
[102] Bjørn.P. Jelle, Accelerated climate ageing of building materials, components and structures in the laboratory, J. Mater. Sci. 47 (18) (2012) 6475–6496, https://doi.org/10.1007/s10853-012-6349-7.
[103] L.A. Escobar, W.Q. Meeker, A Review of Accelerated Test Models, Stat Sci 21 (2006) 552–577, https://doi.org/10.1214/088342306000000321.
[104] R. Nosrati, U. Berardi, Long-term performance of aerogel-enhanced materials, Energy Procedia 132 (2017) 303–308, https://doi.org/10.1016/J.EGYPRO.2017.09.733.
[105] J. Frick, N. Sakiyama, M. Stipetic, H. Garrecht, Large Scale Laboratory and Field Tests of Aerogel Renders. XVInternational Conf. Durab. Build. Mater. Components, Barcelona: 2020. https://doi.org/10.23967/dbmc.2020.089.
[106] N.R.M. Sakiyama, J. Frick, M. Stipetic, T. Oertel, H. Garrecht, Hygrothermal performance of a new aerogel-based insulating render through weathering: Impact on building energy efficiency, Build. Environ. 202 (2021) 108004, https://doi.org/10.1016/j.buildenv.2021.108004.
[107] J. Maia, M. Pedroso, N.M.M. Ramos, I. Flores-Colen, P.F. Pereira, L. Silva, Durability of a New Thermal Aerogel-Based Rendering System under Distinct Accelerated Aging Conditions. Mater 14 (18) (2021) 5413, https://doi.org/10.3390/ma14185413.
[108] A. Morgado, A. Soares, I. Flores-Colen, M.do.Rosário. Veiga, M.Glória. Gomes, Durability of Thermal Renders with Lightweight and Thermal Insulating Aggregates: Regranulated Expanded Cork, Silica Aerogel and Expanded Polystyrene. Gels 2021 7 (2) (2021) 35, https://doi.org/10.3390/gels7020035.
[109] S. Barbero, M. Dutto, C. Ferrua, A. Pereno, Analysis on existent thermal insulating plasters towards innovative applications: Evaluation methodology for a real cost-performance comparison, Energy Build. 77 (2014) 40–47, https://doi.org/10.1016/J.ENBUILD.2014.03.037.
[110] FIXIT AG. Preisliste 2020. https://www.fixit.ch/Home/Services/Downloads/Preis (accessed August 12, 2020).
[111] R. Garrido, J.D. Silvestre, I. Flores-Colen, Economic and Energy Life Cycle Assessment of aerogel-based thermal renders, J Clean Prod 151 (2017) 537–545, https://doi.org/10.1016/J.JCLEPRO.2017.02.194.
[112] Savolainen K, Backman U, Brouwer D, Fadeel B, Fernandes T, Kuhlbusch T, et al. Nanosafety in Europe 2015–2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations, Finnish Institute of Occupational Health. 2013.
[113] A. Nel, T. Xia, L. Mädler, N. Li, Toxic potential of materials at the nanolevel, Science (80-) 311 (5761) (2006) 622–627, https://doi.org/10.1126/science:1114397.
[114] M.J. van Bommel, A.B. de Haan, Drying of silica aerogel with supercritical carbon dioxide, J. Non Cryst. Solids 186 (1995) 78–82, https://doi.org/10.1016/0022-3093(95)00072-0.
[115] Aspen Aerogels Industrial Aerogel Insulation - Home 2019. https://www.aerogel.com/ (accessed October 28, 2019).
[116] Cabot Corporation | Specialty Chemicals and Performance. Health information-Cabot aerogel product 2019. http://www.cabotcorp.com/ (accessed October 28, 2019).
[117] S. Brunner, J. Wernery, M.M. Koebel, High performance thermal insulation - Examples from the Swiss built environment, Cisbat 2015 (2015) 39–44.
[118] Architects.ch. Architects.ch 2018. https://www.architectes.ch/fr/ (accessed August 12, 2020).
[119] AGITEC. Aerogel-Dämmstoffein der Praxis n.d. https://www.energie-cluster.ch/admin/data/files/file/file/1266/ig-hlwd-14-04_agitech-baeschlin-aerogel-anwendungen.pdf?lm=1463752388 (accessed August 12, 2020).

[120] T. Béjat, D. Therme, Experimental Analysis of the Hygrothermal Performance of New Aerogel-Based Insulating Building Materials in Real Weather Conditions: Full-Scale Application Study. vol. 163. Springer Singapore; 2020. https://doi.org/10.1007/978-981-32-9868-2.
[121] T. Stahl, K.G. Wakili, E. Heiduk, Stability Relevant Properties of an SiO2 Aerogel-Based Rendering and Its Application on Buildings. Sustain 2021, Vol 13, Page 10035 2021;13:10035. https://doi.org/10.3390/SU131810035.
[122] S. Fantucci, E. Fenoglio, V. Serra, Laboratory Vs Field Performance of Innovative Thermal Insulating Plasters. XV Int. Conf. Durab. Build. Mater. Components. Eb. Proc., CIMNE; 2020. https://doi.org/10.23967/dbmc.2020.178.
[123] M. Zimmermann, Sustainable Renovation of Historical Buildings (SuRHiB), Nachhaltige Erneuerung historisch wertvoller Bauten. (2013).
[124] M. Guizzardi, Hygrothermal Performance Assessment of Novel Interior Insulation, Solutions (2014), https://doi.org/10.3929/ethz-a-010277871.
[125] M. Guizzardi, D. Derome, D. Mannes, R. Vonbank, J. Carmeliet, Electrical conductivity sensors for water penetration monitoring in building masonry materials, Mater. Struct. Constr. 49 (7) (2016) 2535–2547, https://doi.org/10.1617/s11527-015-0666-7.
[126] M. Guizzardi, J. Carmeliet, D. Derome, Risk analysis of biodeterioration of wooden beams embedded in internally insulated masonry walls, Constr. Build. Mater. 99 (2015) 159–168, https://doi.org/10.1016/j.conbuildmat.2015.08.022.
[127] X. Zhou, D. Derome, J. Carmeliet, Hygrothermal modeling and evaluation of freeze-thaw damage risk of masonry walls retrofitted with internal insulation, Build. Environ. 125 (2017) 285–298, https://doi.org/10.1016/j.buildenv.2017.08.001.
[128] X. Zhou, J. Carmeliet, D. Derome, Influence of envelope properties on interior insulation solutions for masonry walls, Build. Environ. 135 (2018) 246–256, https://doi.org/10.1016/j.buildenv.2018.02.047.
[129] S. Aien, A. Mahdavi, Hygro-thermal implications of the aerogel-based façade insulation layer position and thickness 2019. https://doi.org/10.26868/25222708.2019.210711.