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Laboratory characterization of relative humidity dependent properties for plasters: a systematic review

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Field Code Changed

Abstract

An informed choice of plasters can contribute to improving the comfort and health of buildings users. Therefore, knowing the relative humidity dependent properties to consider when analysing the behaviour of different plasters appears as a fundamental for the selection process, as well as their hygroscopic intrinsic characteristics. A review was conducted on both the test methods and data obtained in literature for a benchmark of more than *200* mineral compositions based on clay, lime, gypsum, cement and combination of those binders. Overall, ranges of response for different plasters, gaps and differences in widespread methods and most common practices of characterization observed in literature were identified and discussed.

Keywords: clay, gypsum, lime, moisture adsorption, moisture buffering, water vapour permeability.

1. Introduction

For almost 50 years, a big impulse on the study of all the elements of influence for Indoor Air Quality (IAQ) has been given due to the link found between a poor IAQ and people's health [1], recognizing effects on occupants like the sick-building-syndrome and building-related illnesses. Relative Humidity (RH) of indoor environment influences thermal sensation and comfort, well-being and health of occupants, from irritation or drying of the mucous membranes to asthma, vocal problems and chronicle respiratory diseases. The desired level of indoor RH for ensuring the best conditions has been identified within the range of *40 - 60%* [2]. In case of RH values above *80%*, a higher risk of biological growth has been pointed out, which can not only be negative for occupant's health or induce distress, but also reduce, in some cases, the expected life time of the building [3]. Furthermore, a passive RH regulation is required in a scenario demanding more and more frequently low energy consumption, embodied and operational. RH indoors depends on several parameters, such as outdoor hygrothermal conditions, occupancy (i.e., period, number of people, kind of activities), ventilation rate, specific constructive solutions, rain penetration, rising dump or built-in moisture. RH regulation can be controlled passively by natural ventilation but, during heating season, this ventilation is commonly minimized not to lose heat. There are evidences that coating materials can be used to moderate the amplitude of RH fluctuation. For these reasons, RH dependent properties of building materials [4] have been studied in the last decades.

Plastering mortars, that based on EN 998-1 [5] are “a mix of one or more inorganic binders, aggregates, water and sometimes admixtures and/or additions” for indoor applications, have an important role both for being widely used and for covering large areas in contact with indoor air. Plastering mortars are commonly composed by a binder, an aggregate and water. Therefore, plasters are building composites. Sometimes their composition includes the presence of bio-products, such as natural fibers, and other additions to improve their properties. A plaster can be applied in one or more layers, with different thicknesses, and often it is coated with finishings, such as a paint system [6-8]. All these factors have influence on the hygroscopic behaviour and permeability of the all-coating system, together with boundary conditions related to the substrate where it is applied, and indoor environment of exposure.

The present study aims to analyse applied methods and respective results for laboratory characterization of RH dependent properties for plasters since in literature a considerable heterogeneity of procedures was detected. For example, hygroscopic behaviour of plasters is related to intrinsic properties of materials like porosity, pore size distribution and bulk density, to properties like surface texture, that are related to application, as well as to RH dependent properties. The latter properties are of more uncertain assessment due to their dependence to indoor microclimatic conditions (RH, T) and time of exposure. The lack of an only protocol for plasters does not promote their homogeneous analysis and, in some cases, affects comparability of results. How to comprehensively characterize plasters response to RH? Which are the methods currently applied and procedures most performed by researchers? What results do we have from literature for different plasters? Are the tendencies of each characteristic similar for the same type of mortars when evaluated by different methods? Therefore, after stating the research questions, eligibility criteria are set to decide inclusion or exclusion of each study. At the end of the selection step, data from 42 articles have been extracted and analysed. Results from about two hundred different plasters were processed and conclusions about the state of art and gaps in literature were lastly presented.

2. Review criteria of selection

This study collects and analyses articles responding to the following criteria:

- Year of publication - Although previous studies exist long ago, it was decided to collect from the publication of *Moisture Buffering of Building Materials*, by Rode et al. [9] in 2005, which set the NORDTEST method, until June 2020.
- Topic - Studies on plasters based on mineral binders such as lime, clay, gypsum and cement, or a combination of those binders were selected. Plaster with special additions like Phase Changing Materials or Super-Absorbent Polymers were excluded since results are considered out of range when compared with plasters with no special addition.
- Methods - If the study met the previous criteria, a laboratory test to determine one or more RH dependent parameters must had been run, to definitively include the article in the review.

The research was conducted on *Web of Science* database with the keywords *plaster*, *experimental*, *moisture*, *MBV*, *WVP*, *adsorption*. According to these search settings, *137* results were found. Applying the referred criteria of selection, *20* of the *137* screened articles were finally selected. To include a larger number of studies, then, the reference list of the already selected articles was checked and, according to the same criteria of exclusion, *22* more articles were included. This implementation method is less time-consuming and permits to include a higher number of articles, although the risk of bias was not assessed. For example, some of the articles included were referenced in other articles of the same research group. Although the risk of slightly affecting statistics, all articles have been included as far as they met the referred criteria. Table 1 presents a synthesis of the *42* articles finally included in the review.

Table 1. Synthesis of articles characterizing plasters for RH dependent properties selected for the review

n	Journal/conference proceeding	Year	Country of 1st author	Main binder	Tested properties	Testing methods
[9]	*Technical University of Denmark. BYG Report*	2005	Denmark	gypsum	MBV	NORDTEST
[10]	*Experimental Thermal and Fluid Science*	2005	Italy	cement	WVP	EN 12086
[11]	*Construction and Building Materials*	2006	Czech Republic	lime	S.I. WVP	ISO 12571 ISO 12572
[12]	*1st Historical Mortars Conference*	2008	Portugal	lime	WVP	EN 1015-19
[13]	*Building and Environment*	2009	Estonia	clay	S.I.	-
[14]	*Construction and Building Materials*	2010	Portugal	gypsum lime	S.I. MBV WVP	ISO 12571 NORDTEST ISO 12572
[15]	*Applied Thermal Engineering*	2011	Egypt	clay	S.I.	ISO 12571
[16]	*XII DBMC- International Conference on Durability of Building Materials and Components*	2011	Portugal	gypsum lime	S.I. WVP	- EN 1015-19
[17]	*Construction and Building Materials*	2012	Czech Republic	lime	WVP	-
[18]	*Construction and Building Materials*	2012	Czech Republic	lime	WVP	-
[19]	*Building and Environment*	2013	Italy	clay	S.I. WVP	- ISO 1015-19
[20]	*4th European Conference of Mechanical Engineering,*	2013	Czech Republic	lime	WVP	-
[21]	*HMC13 - 3rd Historic Mortars Conference*	2013	Portugal	lime	WVP	ISO 12572
[21]	*Energy and Buildings*	2014	Portugal	cement lime	MBV WVP	NORDTEST EN 1015-19
[22]	*5th International Conference on Non-conventional Materials and Technologies*	2015	U.K.	clay	MBV	ISO 24353
[23]	*Construção magazine*	2015	Portugal	clay	S.I. WVP	DIN 18947 -
[24]	*Building and Environment*	2016	France	lime	S.I. MBV WVP	ISO 12571 NORDTEST ISO 12572
[25]	*International Journal of Heat and Technology*	2016	Italy	clay	S.I. WVP	ISO 12571 EN 1015-19
[26]	*Applied Clay Science*	2016	Italy	clay	S.I.	UNI 11086
[27]	*Key Engineering Materials*	2016	Portugal	clay	S.I.	DIN 18947
[28]	*Journal of Materials in Civil Engineering*	2016	Portugal	clay	S.I. WVP	DIN 18947 -
[29]	*RILEM Bookseries*	2016	Portugal	clay	S.I.	DIN 18947
[30]	*II Simpósio de Argamassas e Soluções Térmicas de Revestimento*	2016	Portugal	clay	S.I.	DIN 18947
[31]	*Energy and Buildings*	2016	Czech Republic	cement	MBV WVP	- -
[32]	*Building and Environment*	2016	Spain	clay	MBV WVP	NORDTEST ISO 12572
[33]	*4th Historic Mortars Conference (HMC 2016)*	2016	U.K.	lime	WVP	EN 12086

[34]	*Materials and Structures/Materiaux et Constructions*	2017	France	clay	S.I. WVP	ISO 12571 ISO 12572
[35]	*Energy Procedia*	2017	Estonia	clay	S.I. MBV WVP	ISO 12571 - EN 1015-19
[36]	*Materials*	2017	Italy	cement	MBV WVP	NORDTEST EN 1019-15
[37]	*International Journal of Architectural Heritage*	2017	Italy	clay	WVP	-
[38]	*Cold Climate HVAC 2018*	2018	Estonia	clay	S.I. WVP	ISO 12571 EN 1015-19
[39]	*Building and Environment*	2018	U.K.	clay	MBV WVP	ISO 24353 ISO 12572
[40]	*Construction and Building Materials*	2018	Italy	clay	S.I. WVP	ISO 12571 EN 1015-19
[41]	*Building and Environment*	2019	China	gypsum	S.I. MBV WVP	ISO 12571 NORDTEST ISO 12572
[42]	*3rd International Conference on Bio-Based Building Materials*	2019	France	clay	MBV	NORDTEST ISO 24353
[43]	*IOP Conference Series: Materials Science and Engineering*	2019	France	clay	MBV	NORDTEST
[44]	*IOP Conference Series: Materials Science and Engineering*	2019	Czech Republic	cement lime	WVP	ISO 12572
[46]	*Construction and Building Materials*	2020	U.K.	clay	S.I. MBV	DIN 18947 NORDTEST
[47]	*Construction and Building Materials*	2020	U.K.	clay gypsum lime	S.I. MBV WVP	- NORDTEST ISO 12572
[48]	*Construction and Building Materials*	2020	Portugal	clay cement gypsum	S.I.	DIN 18947
[49]	*International Journal of Architectural Heritage*	2020	Portugal	clay	S.I.	DIN 18947
[50]	*Materials Letters*	2020	Italy	gypsum	WVP	ISO 12572

Notation: S.I. – sorption isotherms; MBV – moisture buffering value; WVP – water vapour permeability.

The journal with higher number of publications included in the review is *Construction and Building Materials*, covering *19%* of the studies, followed by *Building and Environment* with *14%*. Still, *26%* of the studies are from conferences proceedings. Moreover, *29%* of affiliation institution of the first author are located in Portugal, *20%* in Italy, *15%* in Czech Republic, *12%* in UK, *10%* in France and *7%* in Estonia. A predominance of European Mediterranean countries exists, that may be linked to energy poverty as those countries have a large number of buildings with lack of thermal insulation. The number of articles testing the considered properties has increased mostly from 2016 on, as displayed in Fig. 1(a), most probably related with increased concern with indoor comfort and energy efficiency.

The characterization of RH dependent properties for plasters commonly passes through the evaluation of adsorption and desorption mechanisms, moisture buffering capacity and WVP. Other connected characteristics are sometimes investigated, such as pore size distribution, surface film resistance [35], moisture penetration depth [40] or moisture diffusivity [25]. Although not all the studies consider all mechanisms at once, they frequently report a combination of several of those. As displayed in Fig. 1(b), around *22%* of considered articles test only adsorption mechanism (in some cases combined with desorption), the same percentage of articles only WVP, *17%* both these properties, and circa *15%* water vapour adsorption, permeability and moisture buffering together. Regarding the binders selected by authors, the percentage distribution is displayed in Fig. 1(c): plasters based on clay are prevalent, covering *45%* of the studies though gypsum and lime-based plasters are observed at *13%* and *15%*, respectively. Stabilized earth plasters and multi-binder based ones cover only small percentages. The clay plaster is observed in a high number of studies probably due to its acknowledged high hygroscopic capacity, already discussed by Padfield [51] 20 years ago.

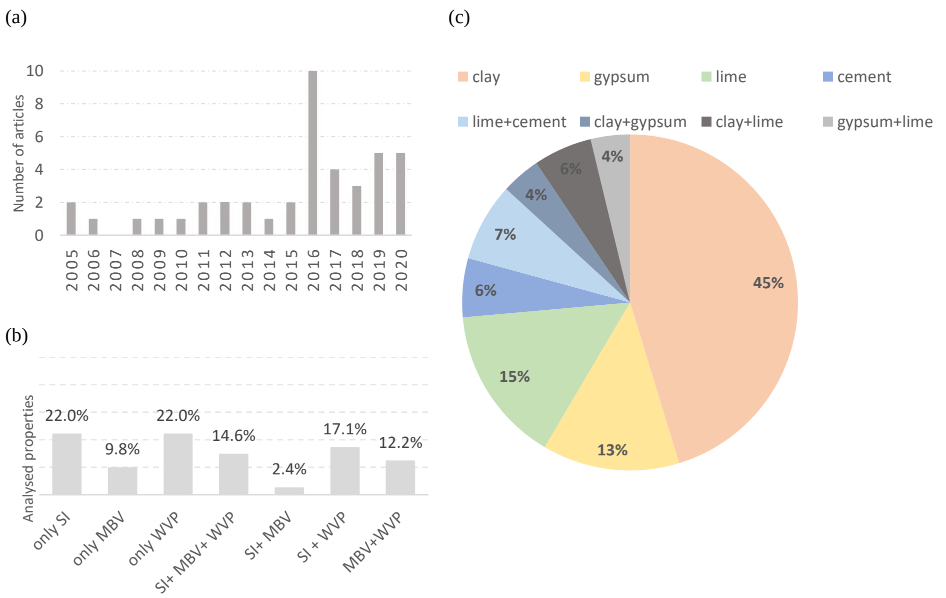

Fig. 1. Temporal distribution of selected articles (a); analysed properties: SI – sorption isotherms; MBV – moisture buffering value; WVP – water vapour permeability (b); percentage distribution of detected plastering mortar by binders (c)

3. Observed methods for characterization

The response of plastering mortars to indoor air RH fluctuations in isothermal conditions can be investigated and described through several methods. Sorption isotherms display moisture adsorption and desorption as a function of the exposure time or of the increasing RH. The procedure would test adsorption for an increase of RH and, otherwise, desorption. Methods apply a RH variation to a specimen already stabilized at another RH stage and quantify the moisture content adsorbed or desorbed. These procedures would give a partial information about the hygroscopic behaviour of the material. In the attempt to approximate real conditions, also stress must be included in the study. This parameter is introduced by the characterization of moisture buffering. The ability of the material to adsorb and desorb moisture in this case is tested through cycles repeated several times. One cycle consists in adsorption and desorption. The methods prescribe a determined duration for each cycle phase, the RH conditions and the minimum number of cycles. Thus, through moisture buffering it is possible to know which would be the response of the material under repeated phases of adsorption and desorption, namely if hysteresis occurs. The moisture behaviour of a plaster would depend on many intrinsic properties, i.e. dry bulk density, porosity, pore size distribution, but to be tested in a correct way it is important to evaluate the thickness involved in the mechanism of moisture penetration. In fact, the specimen has to be thick enough to allow the mechanism being fully activated. The water vapour permeability will give knowledge of the thickness involved in the moisture penetration mechanism. Thus, this property is also considered specific of hygroscopic behaviour. More details on the methods and discussion will be presented.

3.1 Sorption isotherms

The sorption isotherms are curves displaying the moisture adsorption and desorption of a material tested at a fixed temperature. Moreover, it is possible to test the material at one RH increase (and vice versa) for a determined period of time or at multiple increasing RH steps, each one kept until constant mass is achieved. The first procedure can be referred as a one-step or single-cycle method, the second one as a multi-step. Although both procedures aim to describe sorption behaviour of materials, the duration of the test is fixed in one-step method and unknown (depends on materials' response) in multi-step procedure. This first difference can have, eventually, an impact on the choice of one method or the other, i.e. in case of short time available for laboratory characterization, one-step can be more suitable. Even if single and multi-step methods are both used for testing moisture sorption, they cannot be considered equivalent as a direct result. They are rather complementary since one sets out equilibrium moisture content for given RH stages and the other permit to know the moisture content after a determined period of exposure to one selected RH step. Usually these last two parameters (time of exposure and RH conditions) depends on the environment. A short description of existing methods is here presented to enable the comparison.

The DIN 18947 [52], was found in *34.8%* of the cases, the ISO 12571 [53] was adopted by *43.5%* of the studies and the ISO 24353 [54] was not observed in the selected literature. Moreover, *8.7%* of the articles did not specify the standard adopted and the rest (*13%*) referred to other methods. Approximately *70%* of works testing adsorption also perform desorption. Furthermore, in the section 3.1.2 some differences of execution for the same test method are referred.

- 3.1.1 Methods for sorption isotherms

DIN 18947

The German standard DIN 18947 [52] describes a one-step procedure specifically defined for earth plasters. After preconditioning the specimens at 50% and 23°C, temperature is kept constant and RH is set at 80% and maintained for the exposure time of 12 h. During the 12 h the standard prescribes five weighing at different, specified, times, and the class of plasters´ hygroscopicity is achieved by comparing the mass increase of the specimens, 15 mm x 200 mm x 500 mm, on metallic moulds, per exposed area (of 1000 cm^2) with limits defined by the standard along the period of test.

ISO 24353 – part for one step method

The ISO 24353 [54] standard describes a single cycle procedure. The prescribed dimension for specimens is at most 250 mm x 250 mm but not less than 100 mm x 100 mm. Thickness is not specified, deferring to the thickness of the product under test. The standard considers three RH conditions: low, middle and high RH. Temperature should be set at 23±0.5 °C and RH for preconditioning can be 30%, 50% or 70% depending on the RH condition chosen for the test. After a period of preconditioning, when constant mass is reached (the rate of increase in mass does not exceed 0.01g in 24 hours), the adsorption process can start (55%, 75% or 95% RH) and lasts 12 hours. At the end of the 12 hours the desorption process should start with RH set at lower levels (namely 30%, 50% and 70%). Consecutive weighing (10 min intervals) is prescribed. The water vapour surface resistance when running the test should be set equal to 13.3 ±1.3 m^2.h.Pa/µg. This parameter was found strongly influencing the response of bio-based and earth-based building materials [35] and its inclusion in the standard has a relevant role in homogenising results.

ISO 12751

The ISO 12751 [53] standard is addressed to building materials and products for the determination of hygroscopic sorption properties. The prescribed dimension for specimens is a minimum mass of 10 g and, for materials with low dry density, a minimum area of 100 mm x 100 mm is defined for specimens. Two conditioning methods are accepted: desiccator and climatic chamber. Results can be expressed as moisture content mass by mass, mass by volume and volume by volume. Starting conditions of specimens is constant dried mass for adsorption phase and 95% RH for desorption. A minimum of four steps in the range of 30% to 95% RH is prescribed, each one kept until constant mass of the specimen is reached. Desorption process is ended with specimens dried to constant mass. Temperature of testing is 23±0.5 °C or 27±0.5 °C in tropical countries although other temperatures are accepted for testing specific conditions.

- *3.1.2 Discussion on sorption isotherms*

One-step methods are chosen from *39%* of the selected literature testing sorption mechanism. The majority of the collected articles applying one-step methods adopts a modified version of DIN 18957 [52], adding the same procedure (inverted) to test also desorption [30] evidencing a lack of the standard. Another important adjustment observed regards the duration of moisture loading phase (and unloading, when tested): nearly half of the sources are keeping RH level for 24 h instead of only 12 h. Probably the reason is that testing clayish plasters their hygroscopic capacity is not saturated after the prescribed 12 h and neither after 24 hours [24]. This detected practice can indicate that the adsorption period must be extended to completely describe earth plasters potential moisture adsorption. However, the duration of the loading phase can depend on observed indoor RH fluctuations (namely 12 h as a maximum), in which case the introduction of the desorption phase and other RH conditions may be suggested. Adsorption results of one-step method found in literature are all expressed in *g/m^2* and dimensions of the specimens are mostly 500 mm x 200 mm x 15 mm with only one face of 1000 cm^2 exposed [52]. These are big specimens, that occupy large space in climatic chambers and that need stable moulds not to be damaged when handling. In Table 2 some parameters referring to experimental setting conditions are summarized.

Multi-step methods are chosen by *60%* of the authors, *71%* of which follow the ISO 12571 [53] test procedure. The curve is displayed starting from dry state [25,35,47] or equilibrium at 30% RH [14,16,41] and the highest RH is observed in the range 80-97% [41,42]. The duration of the test mainly depends on the specimen (size and plaster composition). Observed specimens are very heterogeneous in terms of thickness, shape and dimensions of the exposed exchanging surface: cylinder with diameter of 100 mm and thickness of 24 mm [36] or diameter and thickness measuring the same (70 mm) [25], prisms of 60 mm side and 6 mm thickness [14] or 40 mm side and 10 mm thickness [26]. The methods adopted to run the test are indistinctly desiccator and climatic chamber, at times together (very high and low RH levels reached by desiccator and middle ranges by climatic chamber). When water vapour film resistance is not considered the wide variation of specimens' size as well as the free interchanging of equipment can affect results. Also, heterogeneous expression of results has been reported. The observed outputs are moisture content percentage (%) in *53.3%* of the studies, mass by volume (kg/m^3) in *26.7%* of the cases, mass by surface (g/m^2) in *13.3%* of the studies, and mass by mass (kg/kg) in the remaining *6.7%* cases.

Table 2. One-step and Multi-step methods observed conditions (referenced in Table1).

		$Area_{specimen}$ [mm^2]	$Dimension_{specimen}$ [mm]	$Thickness_{specimen}$ [mm]	T [°C]	RH [%]	Duration [h]
One-step	*min*	6362	ø 90	10	20	50	12
	max	100000	500x200	20	23	80	36
	mode	100000	500x200	15	23	-	12
Multi-step	*min*	300	10x30	6	20	0.0	Until steady-state
	max	24025	155x155	70	25	97.3	Until steady-state
	mode	7854	ø 100	10	23	97.0	Until steady-state

3.2 Moisture buffering

The moisture buffering performance of a plaster in an indoor environment is the ability of the building material to capture and release water vapour from the air. It is related to the exposed surface and thickness of the material combined with the moisture production of the room and air change ratio [9]. To test this performance, many procedures have been developed: the NORDTEST [9] which has been adopted for the majority of the studies (*71.8%*); the Japanese standard JIS A 1470-1 [56], not observed in selected articles; the standard ISO 24353 [54] used in *15.6%* of the cases.

- *3.2.1 Methods for moisture buffering*

NORDTEST protocol

The method was developed running a round-robin test in laboratories of four universities partners of a project, proving the reliability of the procedure. The test applies RH variation from 33% (16 hours) to 75% (8 hours) with a temperature fixed at 23°C, simulating the daily use of a room (8 hours sleeping; 16 hours waked up) in North European countries. The test requires a minimum of three stable cycles (mass variation not exceeding 5% from one day to another) to calculate the final value. Furthermore, the protocol points out 5 different levels of MBV classification, from negligible to excellent, producing a simple scale for comparison (Table 3).

Table 3. MBV classification from NORDTEST [9] method.

MBV class	Negligible	Limited	Moderate	Good	Excellent
Minimum MBV [$g/(m^2 \cdot \%RH)$]	0	0.2	0.5	1.0	2.0
Maximum MBV [$g/(m^2 \cdot \%RH)$]	0.2	0.5	1.0	2.0	>2.0

Besides this cyclic test to calculate MBV in a practical way, the protocol developed a method, based on heat transport theory, to calculate an ideal MBV through some material properties (dry density, water vapour permeability) determined at equilibrium under stationary conditions. The ideal MBV is calculated from moisture effusivity b_m ($kg/(m^2 \cdot Pa \cdot s^{1/2})$), which depends on WVP. Additionally, when calculating MBV_{ideal} the thickness must be higher than moisture penetration depth and, to guarantee that ideal and practical MBV are similar, it is recommended that the tested material is homogeneous and thickness exceeds penetration depth in both cases. For that, preliminary data on penetration depth of different binder-based plasters will be needed. The protocol also gives prescription on the surface film resistance, recommended to be 5.0 x 10^7 m^2.s.Pa/kg.

ISO 24353 – part for moisture buffering

For cyclic test the standard follows the same prescriptions for specimens, apparatus and water vapour surface resistance described for single test in section 3.1.1. Temperature should be set at 23±0.5 °C and RH for preconditioning can be chosen between 43%, 63% or 83% corresponding to low, middle and high RH levels, respectively. According to RH condition chosen, adsorption should be run at 55%, 75% and 95% RH and desorption at 30%, 50% and 70% RH. Each cycle must be performed at constant temperature and keeping each RH level during 12 hours' adsorption and 12 hours' desorption. The standard prescribes to run four cycles. Weighing follows the same prescriptions than the single cycle procedure. Results are expressed as moisture adsorption content (kg/m^2), desorption content (kg/m^2) and difference between these two contents (kg/m^2). Thus, only the desorption of the third cycle and adsorption and desorption of the fourth are considered by the standard and only under the three RH conditions referred.

JIS A 1470-1

The Japanese Industrial Standard JIS A 1470-1 [56] firstly introduces loading/unloading phases of the same duration (24 hours each) and specifies three alternative humidity conditions. It gives prescriptions about the material surface film resistance to be equal to 4.8±0.48 ·10^7 m^2.s.Pa/kg [4] and thickness of specimen to be the same as the recommended application thickness of the tested product. Preconditioning is the same than for ISO 24353 [54] and, keeping constant temperature, RH steps can be 33-53%, 53-75% or 75-93%, according to the chosen RH condition.

- *3.2.2 Discussion on moisture buffering methods*

The NORDTEST protocol introduced the moisture buffering value and its classification scale. Moreover, it is the only method that provided a way to calculate a practical value for every chosen step of RH. Thus, following this protocol, the results are expressed as moisture adsorption or desorption content referenced to the ΔRH applied. The moisture buffering value is, therefore, less influenced by the chosen RH conditions and comparison of values is easier. Furthermore, it needs to be investigated if the mechanism of moisture behaviour is similar when tested at different RH steps for plasters. The totality of the articles when applying NORDTEST [9] used the same RH conditions than the protocol (33-75% RH) which correspond to low humidity according to ISO 24353 [54], representative of indoor for Nord European countries. Another innovation introduced by the protocol is the prescription for the specimens' thickness to be fitting its moisture penetration depth. To know the moisture penetration depth of specimens, some researchers run NORDTEST at different thickness [35,43,46] and results are discussed in section 4.2. From the analysed literature, thickness and exposed area of the plaster samples are found quite variable from an experiment to another. The most common dimensions for plasters are squared area of 150 mm side and thickness of 20 mm (Table 4).

The ISO 24353 [54] is observed in less cases and, when followed, the middle RH condition is the most commonly used. The shape and size of specimens are found homogeneously as squares of 150 mm side (Table 4). The thickness is found quite variable and the same discussion on optimal thickness introduced by NORDTEST can be found [40]. Moreover, one of the analysed articles [43] applied both NORDTEST [9] and ISO 24353 [54] methods, recording some differences in results: for the same clay-based plaster, MBV values correspond to *1.5* g/(m^2·%RH) if run by NORDTEST and *1.9* g/(m^2·%RH) when run by ISO procedures.

Table 4. NORDTEST [9] and ISO 24353 [54] methods observed conditions (referenced in Table 1).

		A_{sample} [mm^2]	$Dimensions_{sample}$ [mm]	$Thickness_{sample}$ [mm]	T [°C]	RH [%]	n° cycles
NORDTEST	*max*	62500	250x250	80	23	75	20
	min	7854	ø 100	10	11	33	4
	mode	22500	150x150	20	23	-	4
ISO 24353	*max*	22500	150x150	40	23	75	4
	min	22500	150x150	2	23	50	4
	mode	22500	150x150	20	23	-	4

Some studies apply a controlled airflow rate when testing moisture buffering of materials, as referred in Table 5. In fact, this parameter could affect MBV. Cascione et al. [47] refers important differences between laboratory steady-state conditions and real ones (simulated by modelling) where ventilation, moisture transport and other mechanisms are considered. Shi et al. [42] analyses different responses obtained undergoing four different airflow settings (*0.0* m/s, *0.5* m/s, *1.0* m/s, *1.5* m/s) with horizontal or vertical oriented specimens. Adsorption for the vertical group of specimens was higher than for the horizontal ones, especially under maximum airflow conditions. Also, desorption process was influenced by the airflow rate: the higher the flow, the higher the desorption, whereas no big differences between horizontal and vertical position were detected in this phase. For testing plasters, mainly used on vertical surfaces except the ones on ceilings, the experience of Shi et al. [42] should be taken into account as vertical position and controlled settings of airflow rate could lead to different values of adsorption and desorption.

Table 5. Air velocity with plaster specimens placed horizontally, vertically or undefined, in literature studies

Reference	***(Rode et al. 2005)***					***(Mazhoud et al. 2016)***	***(Jiang et al. 2020)***	***(Cascione et al. 2020)***	***(Shi et al.,2019)***	***(Thomson et al. 2015)***
$V_{air,h}$ [m/s]	V_{air} [m/s]	0.05-0.10	0.6	0.50-0.59	0.1-0.3	0.1–0.4	0.1–0.4	< 0.1	0.0; 0.5; 1.0; 1.5	0.1
$V_{air,v}$ [m/s]						0.07–0.14	< 0.15			

3.3 Water vapour permeability

Considering the water vapour transport mechanisms in plasters, WVP (δ) is combined with the analysis of the hygroscopic behaviour nearly in *46%* of the total considered studies. The standards more often referred are ISO 12572 [57] and EN 1015-19 [58], present respectively in about *39%* and *28%* of the articles. The remaining *33%* is divided between some articles not specifying which standard is used and others referring to EN 12086 [59] or to EN 15803 [60] [24,33]. The last two European standards are specific for thermal insulating products and cultural property and will be no further discussed. Thus, for the numbers of data available, only testing procedures of ISO 12572 and EN1015-19 have been here summarized.

- *3.3.1 Methods for water vapour permeability*

ISO 12572

Standard ISO 12572 [57] aims to determine water vapour permeance and/or permeability of building materials and products. It describes the cup test method performed in wet or dry conditions. Circular or square specimens with thickness similar to plasters are used, placed on a cup and sealed. The interior side of the specimen is exposed to a wet or dry conditions, while the assembly is placed in climatic chamber and the other side of the specimen is exposed to a specified RH condition. The exposed area is prescribed to be at least 0.005 m^2 and twice the thickness of the specimen. The thickness can be the same of the recommended application thickness of the product, and in case of homogeneous materials not exceeding 100 mm. The expression of results could be reported as water vapour: permeance w (kg/(m^2·Pa·s), permeability δ (kg/(m·Pa·s)), resistance factor μ (-) and diffusion-equivalent air layer thickness S_d (m). Furthermore, it has been observed that the ISO 12572 [57] refers to Schirmer formula to calculate the WVP of the air, δ_a, required to calculate the water vapour resistance factor ($\mu=\delta_a/\delta$), as equation 1:

$$\delta_a = \frac{0.083 \cdot p_0}{R_V \cdot T \cdot p} \cdot \left(\frac{T}{273}\right)^{1.81} \quad (1)$$

where p_0 is the standard barometric pressure, 1013.25 hPa; R_v is the gas constant for water vapour, 462 N·m/(kg·K); T is the temperature of the experiment, expressed in K; p is the mean barometric pressure, expressed in hPa.

The ISO 12572 [57] also provides a graph for deducing δ_a at 23°C as function of the barometric pressure.

Nevertheless, in the analysed studies the procedure to calculate δ_a is not always expressed and, when it is, sometimes other equations are reported, as the equation 2 from Künzel [64] defined by McGregor *et al*. [35]:

$$\delta_a \approx 2 \cdot 10^{-7} \frac{T^{0.81}}{p_0} \quad (2)$$

or equation 3 from ASTM E96/E96M-10 [61] or EN 15803[60]:

$$\delta_a = \frac{2.3056 \cdot 10^{-5} \cdot p_0}{R \cdot T \cdot p} \left(\frac{T}{273}\right)^{1.81} \quad (3)$$

where p_0, T and p are the same parameters than in equation 1 and R is the gas constant for water vapour, 462 N·m/(kg·K).

The value of δ_a calculated using the referred equations, with conditions of 296 K temperature and standard barometric pressure, would be floating between *1.95* and *2.05* E^{-10} kg/(m·Pa·s).

EN 1015-19

The European standard [58] specifies a method for evaluating water vapour permeability of hardened rendering and plastering mortars, unlike the methods introduced so far. Sampling, preparation and storage of specimens is accurately described, due to its specificity for mortars. The specimen is set in test cup and sealed. The area of the circular cup has to be approximately 0.02 m^2 that correspond to approximately 16 cm diameter. Test is run at 20±2°C and 50±5% RH inside a climatic chamber, while inside the cup a saturated solution of KNO_3 (93.2%) for upper hygroscopic range in wet conditions or of LiCl (12.4%) for lower hygroscopic range in dry conditions is used. An air gap of 15±5 mm should be left between the specimen and the surface of the solution. No prescriptions are given about thickness of the test specimen. The assembly (cup + specimen) is weighed at appropriate time intervals until the quantity of water vapour passing through the specimen is constant. Calculation and expression for permeance and permeability are reported in the standard.

- *3.3.2 Discussion on water vapour permeability methods*

The ISO 12572 [57] was found equally performed in dry or wet cup, with only few works publishing results for both. In Table 5 the experimental conditions for various studies are reported. The most common RH used in the dry cup test is 0-50% and in the wet cup is 93-50% (interior-exterior of the cup). The shape and dimension of specimens was observed mainly as circular with a diameter of 100 mm but also square specimens of various size were found. The characterization following EN 1015-19 [58] shows always circular specimens with big differences in specimens´ dimensions (area and thickness, that may be justified by the specimen dimensions defined in a previous version of the standard, where smaller specimens were used) and RH settings among published articles (Table 6). Following one standard or the other, the dry or wet cup test procedures are considered equally valid, representing different test methods to calculate the same material property. However, what happens in the open pores of the specimen from a sorption point of view is not the same: the mechanism changes from molecular adsorption at lower RH levels to capillary condensation at high RH. Exposure at 0-50% or 95-50% RH can introduce differences in response of some hygroscopic plasters, also if based on the same binder [35]. Therefore, results using the wet and dry cups should not be directly compared.

Table 6. ISO 12572 [57] and EN 1015-19 [58] observed conditions (referenced in Table1).

		$A_{specimen}$ [mm^2]	$Dimension_{specimen}$ [mm]	$Thickness_{specimen}$ [mm]	T[°C]	ΔRH_{dry} [%] int-ext	ΔRH_{wet} [%] int-ext
ISO 12572	*max*	44100	210x210	50	23	23-60	95-50
	min	7854	ø 100	10	20	0-23	85-60
	mode	7854	ø 100	20	23	0-50	93-50
EN 1015-19	*max*	17671	ø 150	38	23	12.4-50	100-40
	min	7854	ø 100	10	20	0-50	93.2-50
	mode	-	-	-	20	-	93.2-50

The values of WVP of air (δ_a) calculated from the literature is found as minimum *1.675* E^{-10} and maximum *2.052* E^{-10} kg/(m·s·Pa)). The highest and lowest water vapour resistance factor corresponding to each value of permeability has been therefore displayed through error bars in Fig. 2. The lowest the water vapour permeability of the material, the widest the error when expressing water vapour resistance factor.

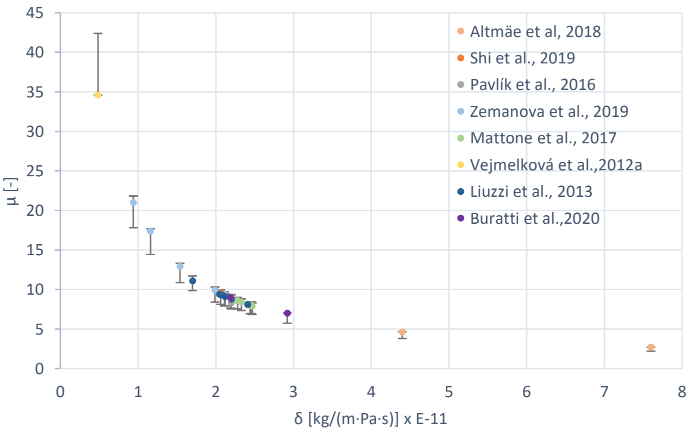

Fig. 2. Correlation between water vapour permeability and resistance factor.

Results obtained from dry and wet cup tests for the same specimens of air lime or clay-based plasters [41, 17,18-20] are considerably different, probably due to capillary condensation in the pores when performing the wet cup test. Fig. 3 presents in light grey values obtained running the wet cup test, compared with full columns in dark grey representing results of the same experiment but with dry cup. The closest pair of values observed for water vapour resistance factor run in both test methods is *9.1-15.1* (about *165%* of increase in the dry cup) and the furthest is *10.95–37.12* (about *340%* of increase in the dry cup). Nevertheless, two out of the three studies here referred were conducted by the same research team on plasters based on lime with additions (metakaolin or grinded bricks) but a greater number of studies is desirable to validate the hypothesis that the two methods are not equivalent for plasters.

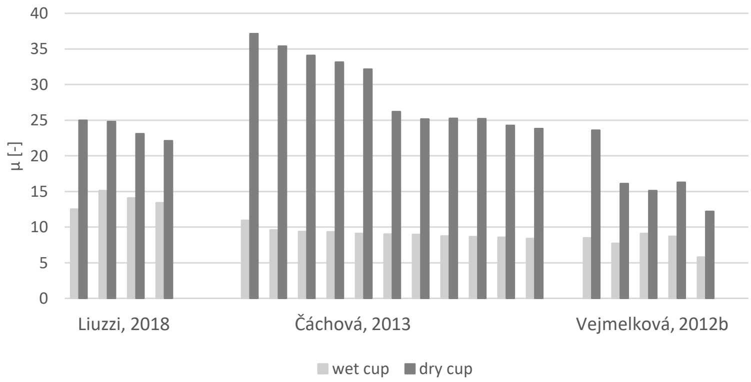

Fig. 3. Water vapour resistance factor (µ) for wet and dry cup test procedures.

4. Data meta-analysis

4.1.Sorption isotherms

The one-step method is mainly used for clay plasters since the DIN 18947 [52] is addressed to this type of plasters but, within the references, also some other binder-based plasters has been tested for comparison [48]. In Fig. 4(a), results (in g/m^2) are reported together with DIN [52] limits for different time of adsorption exposure (6h, 12h, and further for 24h and 36h). In Table A.1 of Supplementary materials more information is reported about considered studies for sorption isotherms. Inside the group of clay plasters there are important differences in terms of compositions. Differences could depend on clay mineralogy [49], addition of bio-aggregates as plant powder [46] or fibers [30,13], sand grain size distribution [28] or added content of other binders [30]. Moreover, some studies were testing the same plaster prepared in different shapes or dimensions [29] or combining more than one of the referred factors [24]. In literature the effect of binders' addition to clay based plasters was found to reduce their adsorption and desorption capacity. Thus, the results reported are in agreement with the expected behaviour, displaying a higher moisture capacity of the unstabilized clay based plaster compared with the stabilized ones. Furthermore, the displayed values of adsorption do not represent the maximum moisture content of clay plasters neither at 36 hours, when the material is still not saturated. Gypsum and cement based plasters, on the contrary, were no longer adsorbing after 12 hours. Maybe 36 hours' duration of loading phase is not considered a realistic simulation, but in winter season under free running conditions in specific areas of unheated buildings in Mediterranean countries, it could happen that RH level is kept around 80% for longer periods [62].

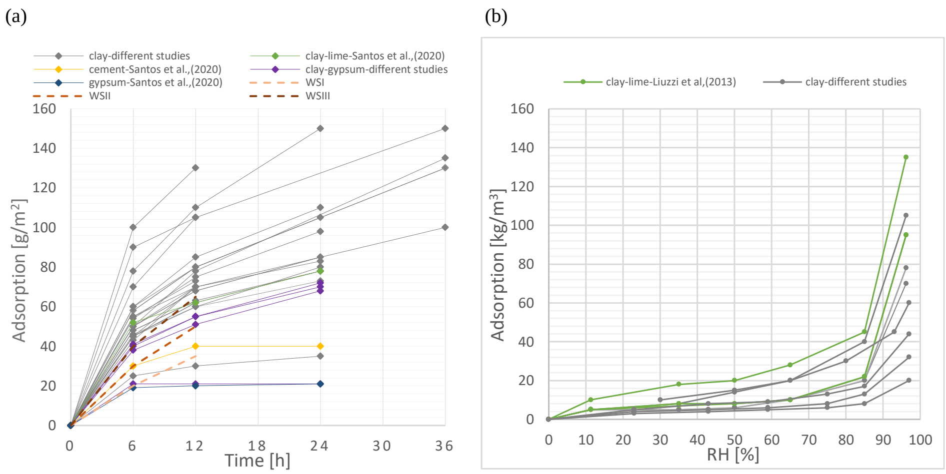

Fig. 4. Adsorption of plasters with different binders for: (a) one-step method and limits of DIN 18947 [52] classes WSI to WSIII at different exposure time; (b) multi-step methods at different RH.

Multi-step tests are run with different levels of RH, chosen by each author from the range suggested by the standard. In some cases a real *scenario* of indoor environment [36] with different occupation and ventilation settings is considered; in other cases standard prescriptions are followed and RH is pushed to 95-97%, values hardly observed in common indoor environment. Values of uptaken moisture (kg/m^3) at successive RH steps of stabilized and unstabilized earth plasters are reported in Fig. 4(b). There is an evident rise in the slope of the curves above 80% RH, emphasized when lime is added, probably due to the activation of another mechanism besides adsorption. Indeed, adding a 5%wt of lime to a clay based plaster results in an increase of moisture adsorbed, namely about a 30% higher than in the plaster without any lime, when the step 85 to 96% RH is considered [19]. The change in the slope often involves hysteresis in desorption, when tested [41,25,35]. This phenomenon, mainly observed for lime or gypsum plasters, has been related by some authors to capillary condensation and possibly to change of microstructure due to additional carbonation of lime [47,14,25]. Moreover, the influence of temperature on the mechanism was rarely investigated; Ashour et *al.* [15] tested various formulations of plasters based on clay with fibers addition, all showing equilibrium moisture content as inversely proportional to temperature. Thus, a small addition of gypsum or lime in plasters can be considered to improve adsorption behaviour of those exposed to high RH and T environmental conditions. Nevertheless, the desorption behaviour should always be tested to ensure there is no decay in moisture buffering capacity when continuous cycles are run.

4.2.Moisture buffering

Dimension of exposed surfaces and RH settings are more homogenous within the analysed literature for MVB evaluations in comparison to all other procedures analysed. A linear correlation between temperature and MBV is observed [25] probably due to the influence of temperature on saturation vapour pressure [14]. To profit all the plaster capacity and provide a correct estimation of MBV, the thickness of the specimens has to be equal or higher than their moisture penetration depth. Laboratory characterization [40] is often conducted to determine the optimal thickness of a plaster. Phelipot-Mardelé et al. [43], testing clay-based plasters with addition of hemp powder and pumice sand, conclude that in specimens *70* mm thick, the phenomenon of moisture penetration is still uncompleted, demanding to further testing campaign. On the contrary, according to Jiang et al. [46], a clay-based plaster incorporating hemp powder shows only plus *15%* of MBV when its thickness is increased from *10* mm to *70* mm, concluding that the first 10 mm of material are responsible for the biggest part of the mechanism. McGregor at al. [35], also testing clay-based plasters, referred the optimal MPD for "fine calcareous-clay" in between *20* and *40* mm and for "kaolinitic clay" in between 10 and 20 mm. Since thicknesses of the tested specimen influences the moisture buffering, in Fig. 5 the MVB (practical) and MBV_{ideal} of observed plasters are presented in function of it. The ideal value of MBV is presented only in five of the considered studies [14,19,32,41,42] following the method proposed from Rode et al. [9]. Despite the limited data, MBV_{ideal} was however included and its values are found in the range of the corresponding practical ones. Based on the literature results, MBV of gypsum plasters is greater for 20 than 10 mm thicknesses, making the former preferable. Instead, lime based plasters keep the same value both for thicknesses of 20 mm as of 80 mm. Thus, 20 mm for application would be advisable to optimize their moisture buffering using the lowest thickness. The same choice applies to clay based plasters, which highest values of moisture buffering are observed for thicknesses of 20 mm. Thus, 20 mm of thickness corresponds to common application practice for a plaster and for the three binders referred can be consider the optimal one for moisture buffering, unless MPD is calculated.

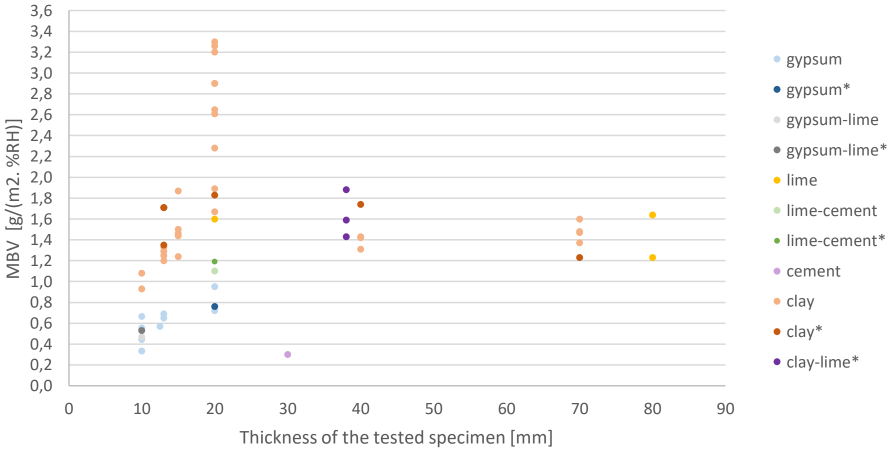

Fig. 5. MBV and MBV_{ideal}(*) for plaster specimens with different thicknesses.

According to NORDTEST [9] classification (Table 3) and based on Fig. 5, it appears that, within the referred literature, there are no plasters with *negligible* MBV; plasters based on gypsum and gypsum-lime have mainly a *moderate* behaviour whereas based on lime and clay-lime correspond to *good* behaviour according to the classification. From the collected significant amount of data regarding clay-based plasters, it is visible that it covers different classes of behaviour, but it is the only material reaching *excellent* classification.

4.3.Water vapour permeability

The WVP test is used in some articles to determine MPD, as referred in the previous paragraph, or to investigate the property itself as another RH dependent-one. Permeability (δ) and resistance factor (μ) observed are resumed in Fig. 6. Some of the reported values have been calculated from the published data available, using a WVP of air (δ_a) of 19.50 E^{-11} kg/(m·Pa·s). The addition of lime or gypsum to the clay based plaster appear to slow down its water vapour permeability. Instead, combination of cement and air lime, often taken with a weight ratio 1:1 [21,44], shows an enhancement of WVP.

Thus, the addition of lime can be a tool to improve the poor permeability of cement. Not many results were found for blended binder-based plasters, requiring further investigation.

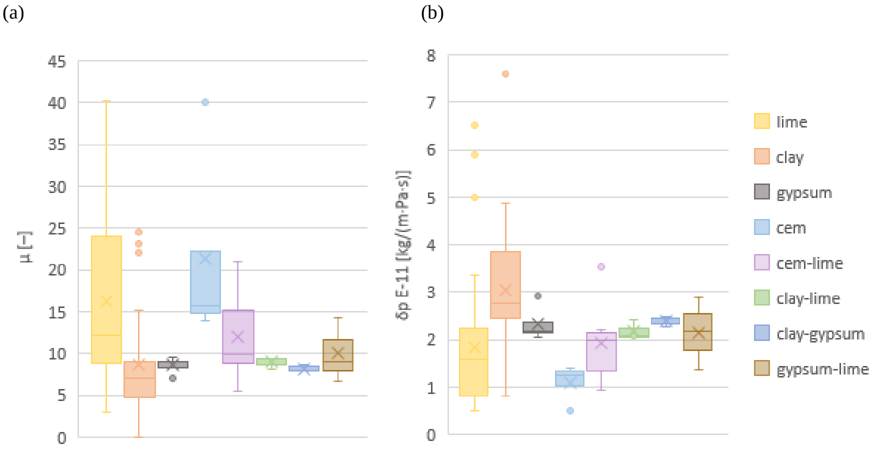

Fig. 6. Water vapour resistance factor μ (a) and permeability δ (b) for different binder plasters (referenced in Table1).

5. Results and discussion

A resume of existing test methods for characterization of RH dependent properties, their most common practices of application and a meta-analysis of results present in literature, has been presented. Moreover, a database of results has been created (Table A.1 - A.3 of Supplementary Materials). Methods have been presented and discussed in section 3 and some strengths and errors have been identified.

DIN 18947 [52] and ISO 24353 [54] were presented as one-step methods, addressed to evaluate the materials' moisture adsorption in a determined period of time and for a chosen RH variation. The ISO standard is considered the most suitable to describe the moisture behaviour of plasters because it admits three different humidity conditions, gives prescriptions on the surface film resistance and includes adsorption and desorption. The German standard, instead, only admit adsorption for a duration of 12 hours. Desorption is not covered by the standard. Thus, the duration of moisture release and the eventual residual moisture content are not investigated when using the DIN18947 [52]. However, the mechanisms of desorption and possible hysteresis of the material are important to fully understand its response to RH fluctuations and were, indeed, implemented in many of the studies. Moreover, only one range of RH condition is considered by the DIN standard (most probably common in German buildings) whereas indoor microclimate can present many different scenarios in other countries. Nevertheless, a more detailed prescription on thickness of the tested product in case of plasters, recommending it to be higher than the moisture penetration depth, should be added to the recommendations of both standards. Moreover, to facilitate comparison of results from different studies it could be preferable the expression of results in terms of gained mass per volume (rather than area). Multi-step methods aim to describe the moisture behaviour at equilibrium moisture content of materials. The ISO 12571 [53] prescribes the range of RH exposure 0-95% and admit the use of climatic chamber or desiccator indiscriminately. Nevertheless, to reach low and high stages of RH, is common practise the use of desiccator due to technical difficulties in reaching this values of RH by the climatic chamber. This turns the use of both in the same laboratory characterization a widespread practice, although in climatic chamber the air velocity would be higher than in desiccator and it was already observed [55] that the air flow can have big effects on adsorption and desorption properties of some hygroscopic materials. A prescription on the air flow inside the chamber would be recommended to ensure a better comparison of the test results. The characterization of moisture buffering introduces the material stress factor in the study. Both NORDTEST protocol [9] and ISO 24353 [54] observed in the analysed literature consider the surface film resistance but NORDTEST implemented prescription on the thickness of the specimen, not present in the international standard. Moreover, the calculation of the value introduced by the protocol, makes the results independent from the chosen RH conditions and gives a tool of easy comparison. Thus, the NORDEST protocol is considered the more accurate of the two. This method, on the other side, is set on indoor hygrothermal conditions of Northern European Countries where, during winter, indoor temperature is considered 23°C and RH fluctuation in between 33% and 75%. However, there are many different situations, according to regional climate and access to energy, that the method may not represent, namely when energy poverty occurs and heating is not continuous during Winter. If water vapour loading and unloading time is considered a fixed parameter (16 hours of activity and 8 hours of sleeping at least for developed countries) the minimum and maximum indoor values of RH and temperature could variate from country to country. Representativeness of the test is questioned for different conditions and eventually different RH ranges. Testing water vapour permeability, both the two methods (ISO 12572 [57] and EN 1015-19 [58]) allow the use of dry or wet cup procedures indistinctly. When testing plasters, the two procedures were found to give different results. Although the ISO introduces the information that "at higher humidities the material pores start to fill with water*"* [57] and transport of liquid water increases, it seems reasonable that for plasters dry cup procedure should be recommended as conservative approach. The European standard [58] is addressed to hardened rendering and plastering mortars and, for this reason, contains more specifications on sampling, preparation and storage of the tested mortars. The circular shape prescribed from this standard seems more accurate for avoiding edges and easily applicable to plasters, cast in moulds. On the other side calculation and expression of results is less meticulously described than in the ISO [57].

Furthermore, the application procedures of each method in the selected literature has been analysed and some heterogeneity observed. In Table 7 a summary of the parameters considered for the comparison is reported. Experimental conditions (T and RH), duration of the experiment and dimensions of specimens (surface and thickness) are the main variables considered. Comparability of results is calculated as the combination of the three previous parameters. The NORDTEST method [9] is the most homogeneous for hygrothermal conditions, test duration and dimensions of specimens. The poorest comparability is reported for hygroscopicity tested according to ISO 12751 [13], where shape, exchanging surface and thickness of the specimens vary a lot from one study to another, and a big diversity of RH steps is observed. All the other methods result mildly comparable.

Table 7. Resume of characteristics for observed applications of methods to test RH dependent properties of plasters.

Method	Property	Conditions	Duration	Dimensions	Comparability	Representativeness
DIN 18947	hygroscopicity	+	-	+	*moderate*	*clay*
ISO 12571		-	n.a.	-	*poor*	*diverse*
NORDTEST	MBV	+	+	+	*good*	*diverse*
ISO 24353		+	+	-	*moderate*	*diverse*
ISO 12572	WVP	-	n.a.	+	*moderate*	*diverse*
EN 1015-19		+	n.a.	-	*moderate*	*diverse*

The rating scale is poor, moderate and good; "+" assigned for homogeneity; "-" assigned for heterogeneity; "n.a." not applicable.

Table 8 reports ranges of results for the various plasters, as found in the reviewed literature. According to the German standard DIN 18947 [52] modified to 24 hours' duration, clay plasters show the highest adsorption of *140* g/m^2 [63].

From the few results available on not-only clay based plasters, it appears interesting that the lowest value of adsorption (*73* g/m^2) for a specific clay plaster with *20%* addition of gypsum [40] results 2 times higher than the lowest value of adsorption for another clay plaster with no addition. The variability of clays' response largely depends on the different mineralogy, turning the observed range of results for this material quite wide. Moreover, expression of results does not consider the thickness of the tested specimen with the risk of providing an inaccurate data. Clay-based plasters show very good adsorption capacity at steady state too, although the highest value is observed for the hemp-lime plasters tested by Mazhoud *et al.* [25], with a hemp-lime mass ratio of 0.15. These plasters show a moisture content of *10%* when stabilized at 97% RH. Without addition of hemp powder, lime plasters show lower hygroscopicity, thus for this binder base it is observed the widest range in between all the reported plasters. Furthermore, it is important to remark the hysteresis phenomenon referred by many researchers particularly for lime-based plasters. Further investigation is suggested for gypsum-lime plasters, once few data were found available and adsorption values appear too low compared with the range of plasters based on single gypsum and single lime. MBV values are all above *0.2* as referred already in section 4.2, with no plaster classified as *negligible* according to the NORDTEST [9] (Table 3). Still, as expected from adsorption results, clay-based plasters show the highest MBV. Ranges are very varied: more than *2* g/(m^2·%RH) for clay, *1* g/(m^2·%RH) for air lime and about *0.50* g/(m^2·%RH) for gypsum plasters. Just one result was found for cement plasters, whereas really small ranges are observed for plasters with more than one binder due to the small number of case studies. WVP is determined for all the different types of plasters, giving the opportunity of a fairer comparison. According to results here reported, the highest value of WVP is observed in clay-based plasters, followed by air lime, lime-cement, gypsum, gypsum-lime, clay-gypsum, clay-lime and cement. Cement shows the lowest WVP. As the low WVP of cement is commonly assumed, the improvement obtained from the combination with lime could be deeper investigated to increase its compatibility with traditional buildings. The lower range limit for gypsum, clay-lime and clay-gypsum plasters are all above *2* E^{-11}kg/(m·Pa·s), that once more could be due to a lack of number of results or to a consistently permeable behaviour.

Table 8. Value or range of values for adsorption, MBV and WVP from literature (referenced in Table 1).

Property	Unit		C	AL	G	CE	C-AL	C-G	G-AL	AL-CE
Adsorption*	[g/m^2]	*max*	140	-	22	40	24	82	-	-
		min	35					73		
Adsorption**	[%]	*max*	6.30	10	3.10	-	-	-	0.98	-
		min	0.10	0.03	0.08				0.16	
MBV	[g/(m^2·%RH)]	*max*	3.3	1.64	0.95	0.30	-	-	0.47	1.19
		min	0.93	0.67	0.33				0.42	1.10
WVP*'	E^{-11}[kg/(m·Pa·s)]	*max*	7.60	6.50	2.92	1.40	2.41	2.47	2.89	3.55
		min	0.8	0.48	2.06	0.49	2.05	2.28	1.36	0.94

AL - air lime; C - clay; CE - cement; G - gypsum; L - lime; *according to DIN 18947 [52] adsorption at 24 hours; **according to ISO 12571 [53]; *' according to ISO 12572 [57] and EN 1015-19 [58] by wet and dry cup all together.

The methods and results until here discussed pave the way for some considerations. The thickness of specimens should be set according to moisture penetration depth. For clay based specimens the thickness is found equal or above *20* mm [35], compatible with common plaster thickness. The referred value could be chosen also for other based plasters where MPD is proved lower or equal than the value and no specific design purposes occur. The round shape attends standard prescription for WVP and remove possible dispersions in sealing the edges while testing adsorption/desorption mechanisms in static and/or dynamic settings. A diameter of 100 mm is here suggested, since it is widely used for WVP and for adsorption/desorption isotherms in multi-step method tests. Moderating and unifying the dimensions of the specimen can improve the efficiency of production and simplify the execution of the tests, i.e. a higher number of specimens can be simultaneously placed in a climatic chamber, quicker response to each step in case of multi-step adsorption/desorption test, higher manoeuvrability. When a dynamic test is run the surface film resistance should be set according to ISO 24353 [54].

6. Conclusion

Indoor moisture passive control performed by plasters is considered nowadays an important goal to improve comfort of occupants, avoid health diseases linked with bad quality of indoor air, and save energy. Thus, it is desirable to consolidate the methods used to characterize plasters in that regard. The present study analyses the principal existing methods for characterization of relative humidity dependent properties, points out variability in the procedures most performed in literature and synthetizes ranges of results for different binder-based plasters.

ISO 24353 and DIN 18947 are the two standards used to characterize adsorption/desorption behaviour by one-step procedure. The first is recommended, as it is found more complete, preferably adding the calculation and use of the optimal specimen thickness. The standard ISO 12571 is used to describe equilibrium moisture content at steady state. Doubts are raised on the representativeness of real conditions for some of the steps prescribed by the standard as they are found really low or high. Furthermore, the standard allows using climatic chamber and desiccator methods indistinctly. This indication results in having the two methods adopted within the same test procedure in common practice, which may provide a poor accuracy of results because of the different air velocity affecting the two environments. For testing moisture buffering the most suitable method is the NORDTEST although further investigations are believed to be necessary to evaluate the validity of this method for different environmental conditions (different duration of exposure and RH levels) that can be typical of non-Northern European Countries. Methods for water vapour permeability are found quite similar, although the European standard EN 1015-19 is addressed to hardened rendering and plastering mortars, thus providing more detailed specifications for plasters. On the other side, the ISO 12572 accurately describes all results calculation and properties that can be determined in relation to the permeability or resistance of building materials to water vapour diffusion. Both standards allow for the use of wet and dry cup indiscriminately. The dataset obtained from literature clearly indicates that for hygroscopic materials the results from one procedure or the other are very different. Hence, the dry cup is preferable as it gives the results in the worst case scenario, i.e. the lowest vapour permeability among the two cup tests. Anyway, it seems that some indication should be provided in both standards, concerning which type of cup should be used or defining that the results must always be provided together with the specific indication of the test condition used, namely the RH inside the cup or, at least, the type of test-cup.

Results from one-step and multi-step methods confirm the high adsorption capacity of clay-based plasters. Cement and gypsum based plasters, instead, show the lowest value of adsorption and the quickest saturation. The influence of the addition of low content of lime or gypsum in clay plasters should be further investigated. Indeed, if it may appear to slightly reduce adsorption capacity when exposed to 80% RH, for higher RH exposures it can introduce an increase in moisture adsorption. Nevertheless, desorption of stabilized clay plasters should be more investigated since the lime and/or gypsum added can cause hysteresis and reduce the moisture buffering. However, most analysed plasters are classified as *good* according to the NORDTEST classification. For clay, lime and gypsum based plasters a thickness equal to *20* mm is found suitable, in case the moisture penetration depth is not calculated. Water vapour permeability of clay, gypsum and lime was found, as expected, better than cement. Thus, cement shows the lowest permeability, which can be significantly improved by adding lime, according to some results.

In order to have consistent results for the most significant RH dependent properties of plasters, apart from the methods selection and improvement suggested, some homogenization of test methods and shapes of specimens should be considered. Specimens with cylinder shape of about *100* mm diameter and *20* mm thickness, when greater than moisture penetration depth, could be adequate for the overall study of RH dependent properties of different types of plasters. However, the application of a plastering mortar on a substrate may change their microstructure and, therefore, their performance when tested for RH related properties. Thus, specimens de-moulded after having being moulded in contact with a substrate should also be tested and validated.

Concluding, for reducing energy consumption while improving indoor air quality and comfort, the contribution of plasters for RH related properties can be considered. Furthermore, to permit a fairer comparability of different plastering solutions, it emerges the need of a standardised protocol designed to fully describe plasters in their dependence on the considered RH conditions. Finally, the use of clay-based plasters appears very promising in this regard.

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