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Hygric properties of porous building materials: Analysis of measurement repeatability and reproducibility

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ABSTRACT

Material properties are crucial input parameters for the analysis of heat, air and moisture transfer phenomena in built environment. However, many round robin tests reveal that the measurements on material properties – especially hygric properties – have poor reproducibility. Thus the measurement and data analysis methods should be questioned, and the currently available databases for material properties are not perfectly reliable.

In this paper we aim at analyzing the material errors, repeatability errors, between-lab errors and reproducibility errors involved in the determination of hygric properties of porous building materials. The same materials as those used in the EC HAMSTAD project – autoclaved aerated concrete, calcium silicate board and ceramic brick – are chosen as target materials in our tests to facilitate error analysis. Static gravimetric tests, cup tests, capillary absorption tests, vacuum saturation tests and pressure plate tests have been repeated three times under repeatability conditions. Then the experimental results are analyzed in combination with the EC HAMSTAD report to calculate various errors. Results show that different materials have different heterogeneity errors, which can hardly be avoided. Moreover, in general these tests have excellent repeatability, indicating that under proper control the tests themselves are trustworthy. However, the large between-lab errors and the subsequent poor reproducibility demonstrate that in different labs the experimental procedures, condition controls, as well as data processing methods can deviate significantly. As a result, stricter and more detailed instructions are needed to improve the reproducibility of the tests for determining the hygric properties of porous building materials.

1. Introduction

1.1. Background

Moisture transfer is one of the most classic topics in building physics. Many issues, such as indoor air quality [1–3], the service life of building components [4–6], and the energy efficiency of buildings [1,3,7,8] are all closely related to moisture transfer processes.

To analyze moisture related phenomena, the hygric properties of materials are indispensable input parameters. Large scale campaigns aiming at the determination of the hygric properties of porous building materials – such as EC HAMSTAD [9], IEA Annex 24 [10] and ASHRAE Research Project 1018-RP [11] – started out about two decades ago and have obtained encouraging achievements. Relatively complete databases have been established in western countries.

Unfortunately, these databases are not flawless. One of the most challenging dilemmas is the fact that the test results of the same material can be quite dissimilar in different labs, as revealed by many round robin tests. For instance, in the EC HAMSTAD project, six labs participated in the round robin tests for various material properties of autoclaved aerated concrete (AAC), calcium silicate

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board (CS), and ceramic brick (CB). The outcomes demonstrated that non-negligible deviations exist between the results from different labs, especially for the actual hygric properties [9]. Another case in point is the IEA Annex 41 project. In its Subtask 2, 14 participating labs measured the hygroscopic properties – sorption isotherms and vapor permeabilities – of uncoated and coated gypsum board. Again the results from different labs showed impressive divergences [12].

The poor reproducibility of hygric properties exerts a negative impact on both scientific research and engineering practice, as it poses a threat to the reliability of any heat-air-moisture (HAM) analysis. For instance, to reliably predict a drying process, sorption isotherms and vapor permeabilities should be determined within 5% and 20% uncertainties, respectively [11]. These requirements, however, can hardly be fulfilled in view of the currently poor reproducibility in measurements. Worse still, a drying process is a relatively simple issue, implying that other more complicated HAM processes may require even more accuracy in material properties.

The problem of unsatisfactory reproducibility may have various roots, such as materials' heterogeneity, test methods' inherent uncertainty, variant faculty and facilities, as well as differences in experimental procedures and data analysis methods. A better understanding of these errors is needed in order to identify the key problem and formulate solutions to it. Before articulating the objectives of the paper, we first shortly introduce the error analysis used in this paper.

1.2. Basics for error analysis

Errors exist in all measurements, as no test is perfectly reliable. Accuracy describes the reliability of measured results, and it covers two aspects – trueness and precision. Trueness represents the closeness between the average result and the true or accepted reference value, and it is often expressed in terms of bias. Precision stands for the agreement between multiple test results, and it is often expressed in terms of standard deviation [14]. Trueness and precision can be distinguished with the help of Fig. 1. Obviously, trueness relates to systematic errors ($e_{systematic}$), while precision describes random errors (e_{random}).

More often than not, trueness can only be estimated because the true value is often unavailable, unless a generally accepted reference value has been prescribed. Consequently, there are not many studies about trueness. On the contrary, precision is much more frequently analyzed, since it involves only measured results. It is influenced by many factors. First and foremost, the heterogeneity of materials should be taken into account. Some materials – such as CS – are well known for their homogeneity. So the results from duplicate CS samples in the same test can be very close to each other. Other materials – such as CB – are not so homogeneous, leading to greater differences.

Besides the errors rooted in the materials' heterogeneity, there are some other influence factors that should be considered. According to the ISO 5725 standard [14], these factors include:

a) the operator;
b) the equipment used;
c) the calibration of the equipment;
d) the environment (temperature, RH…);
e) the time elapsed between measurements.

While not being mentioned in the standard, we assume that

f) the overall experimental procedure plays an important role as well.

If the same samples are used and all factors from a) to f) remain unchanged in replicate tests (a short period of time applies to factor e)), then these test conditions are defined as repeatability conditions and the standard deviation of the results is defined as the repeatability error ($e_{repeatability}$). If the same samples are used but all these factors are different, then reproducibility conditions and reproducibility error ($e_{reproducibility}$) are obtained accordingly [14]. Obviously, reproducibility and repeatability are two extremes of precision.

The round robin tests carried out in various labs – such as the EC HAMSTAD [9] and IEA Annex 41 [12] mentioned above – are perfect examples related to reproducibility, except that the materials' heterogeneity is normally not included in reproducibility but unavoidable in such round robin tests, because usually different samples are used by different labs. Repeatability, on the other hand, has not received much attention. One of the key reasons may be that tests on hygric properties are extremely time consuming, and replicate tests under repeatability conditions are even more exhausting.

With (explicit or implicit) knowledge on systematic and random errors, we can express a measurement result as:

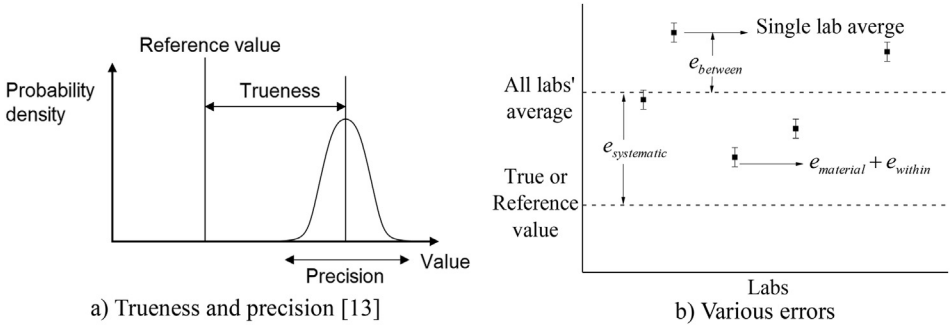
$$x = x_{true/ref} + e_{systematic} + e_{random} \quad (1)$$

where x is a measured value and $x_{true/ref}$ the true or reference value.

$e_{systematic}$ cannot be determined easily, and it is not our primary concern in this study. For more insight into e_{random}, we can develop it further, as is illustrated in Fig. 1:

$$e_{random} = e_{material} + e_{within} + e_{between} \quad (2)$$

where $e_{material}$ is the error caused by materials' heterogeneity, e_{within} the random error caused within a lab (such as the influence of temperature and RH fluctuations of ambient air on the static gravimetric test for sorption isotherms), and $e_{between}$ the between-



a) Trueness and precision [13]
b) Various errors

Fig. 1. Basic concepts for error analysis (Ref. [13] for a)).