Influence of variability in hygrothermal properties on analytical results of simultaneous heat and moisture transfer in porous materials

Yamamoto, Hiroaki

Takada, Satoru

(Citation)
Journal of Building Physics,45(6):757-773

(Issue Date)
2022-05-01

(Resource Type)
journal article

(Version)
Accepted Manuscript

Influence of variability in hygrothermal properties on analytical results of simultaneous heat and moisture transfer in porous materials

Hiroaki Yamamoto, Satoru Takada

Kobe University, Japan

Author Note

Correspondence concerning this article should be addressed to Satoru Takada,

Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe, Hyogo 657-8501, Japan

Tel. +81-78-803-6038

Fax. +81-78-803-6038

E-mail: satoruta@kobe-u.ac.jp

Influence of variability in hygrothermal properties on analytical results of simultaneous heat and moisture transfer in porous materials

Abstract

Depending on the data source used, the material hygrothermal properties that are used in the numerical analysis of simultaneous heat and moisture transfer will not be consistent. Differences in measurement methods and the individuality of specimens account for this. It is necessary to choose values from these different physical property sets to conduct a numerical calculation, which can cause the calculated results to differ. The subsequent range of variation in the calculated results should be quantitatively evaluated. In this study, the physical properties of several types of porous building materials were first gathered from four databases. The data were then categorized based on the kind of material and compared in terms of each physical property (density, porosity, specific heat, moisture capacity, thermal conductivity, and vapor permeability). The density, porosity, and specific heat varied by 10% on average, and the moisture capacity, thermal conductivity, and vapor permeability varied by 20% or more for all types of materials. In particular, the vapor permeability of plywood and moisture capacity of gypsum board differed by 50%.

The influence that these physical property value variations had on hygrothermal calculation results was then quantitatively demonstrated for moisture and heat flow rate under a step change in the relative humidity or temperature of indoor air for a single layer wall. The moisture and heat flow rate into a single layer wall fluctuated by approximately 10% to 40% due to differences in the vapor permeability and moisture capacity of the materials. For all types of materials, moisture was transferred more slowly than heat. Therefore, differences in moisture property values, such as vapor permeability and moisture capacity, influenced the results more significantly. Moreover, the moisture flow was accompanied by a phase change. The differences in moisture property values thus affected the heat flow.

Keywords: hygrothermal properties, simultaneous heat and moisture transfer, numerical analysis, variability, database, porous material, air conditioning load

1. Introduction

The numerical analysis of temperature and humidity distribution inside a wall based on the simultaneous heat and moisture transfer equations has been used for evaluating the air conditioning load, condensation behavior, and indoor thermal comfort of human (Hens, 2007). The accuracy of the analysis depends on the hygrothermal properties of the materials used in the model, in addition to the analytical model of heat and moisture transfer (Barclay et al., 2014) and the boundary conditions (Janssen et al., 2007). When analysis is conducted, those who perform the calculation must choose the physical properties related to heat and moisture transfer. If the correct physical properties are uniquely determined, the procedure is very clear. However, there are typically many potential alternatives for physical properties and those who perform the calculation must select one of them. Variability is thus introduced into this process, which affects the calculation results.

Numerical analysis in the hygroscopic range requires a set of six physical properties: density, porosity, specific heat, equilibrium moisture content, thermal conductivity, and vapor permeability. Measuring each of these physical properties is typically not easy (Feng et al., 2013; Pietrak et al., 2019). Usually, a certain value will be selected for the calculation from existing values listed in physical property databases. There is no established method for selecting a value from the large number of available values, despite their variability.

Available databases include those released by the International Energy Agency (IEA) Annex 24 (Kumaran, 1996), the National Research Organization of Canada (NRC) (Kumaran et al., 2002), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Kumaran, 2002; ASHRAE, 2013), and the Fraunhofer Institute of Building Physics (Kunzel, 1995; Fraunhofer Institute for Building Physics, 2018).

Factors that cause these differences in physical property values have been clarified in some previous studies. In Annex 41 (Roels, 2008), a round robin test was conducted on vapor permeability and equilibrium moisture content. Roels (2008) carried out a comparative investigation based on measured results that differed depending on the organization. He concluded that the magnitude of variability in physical properties depended on the type of specimen, cup, and sealing used for vapor permeability, and on the humidity conditions for equilibrium moisture content. Nishimura et al. (2004) proposed a quantitative calculation method for the uncertainty associated with the measurement of thermal conductivity. This indicated the reliability of the measured results of the physical property.

Feng et al. (2015) classified factors of variability in physical properties into three types: heterogeneity of material, different measuring organizations, and repeatability of measurements in the same organization. They then compared measured results for the physical properties of autoclaved lightweight concrete (ALC), calcium silicate board, and ceramic brick with those reported by the EC HAMSTAD project (Roels et al., 2003). They found that the magnitude of the heterogeneity error differed depending on the material and that the repeatability error in the same organization was small, whereas the error due to differences in measuring organizations was large. Furthermore, Feng et al. (2016) discussed the effect of temperature on physical properties and showed that the physical properties related to liquid water transfer, such as water absorption coefficient and vapor permeability at high humidity, were significantly affected by temperature changes. Feng et al. (2020) compared two measured material properties of ceramic bricks at nine different laboratories based on each of the laboratory's individual experimental and the standardized methods. In the case of the cup test for measuring moisture permeability, the discrepancies between laboratories were reduced by specifying the method. Unlike these previous studies, this present study assesses the influence of variability in physical property on the analysis of simultaneous heat and moisture transfer in the hygroscopic range without considering the variability factors.

Defraeye et al. (2013) evaluated the influence of variability in hygrothermal properties, including liquid water transfer, on the analytical results for simultaneous heat and moisture transfer in the drying behavior of ceramic brick and plaster. This was accomplished by changing the physical property values randomly (Janssen, 2013) according to a normal distribution which was based on the average and standard deviation of physical property values from several organizations (Roels et al., 2004). They compared the 50th percentile (median) and the 5th or 95th percentile of the analytical results, and noted that the variability in the moisture transport properties may affect the drying rate.

Prada et al. (2014) made the same assumption as Defraeye et al. that the variability of the thermal properties followed a normal distribution. They analyzed heat loss from a stone wall or clay block envelope under warm and mixed climates by randomly changing the thermal property values. Using normalization based on the median result, they quantitatively showed the effect of the variability in thermal properties on the monthly mean heat flow through the outer wall of the building in summer and winter.

In the studies performed by Defraeye et al., the variability in physical properties was regarded as constant. However, this may vary for different kinds of materials and physical properties. In this present study, six physical properties necessary for analysis in the hygroscopic range (density, porosity, specific heat, moisture capacity, thermal conductivity, and vapor permeability) from four materials (ALC, concrete, plywood, and gypsum board) were collected from the physical property databases created by four organizations (IEA, ASHRAE, Fraunhofer, and NRC). The differences between physical property values were evaluated without analyzing the reasons for the variability. The effect of the differences in physical properties values on the analytical results for typical heat and moisture transfer problems (a step change in the relative humidity or temperature of indoor air for a single layer wall) were then evaluated. The differences in the solutions that were associated with the choice of the physical property values in the databases were shown quantitatively for the four representative porous building materials.

2. Variability in physical properties of porous materials

2.1 Collection of data from physical property databases

The values necessary for the analysis of simultaneous heat and moisture transfer in the hygroscopic range (density, porosity, specific heat, moisture capacity (Xi et al., 1994), vapor permeability, and thermal conductivity) were gathered from the physical property databases created by IEA, ASHRAE, Fraunhofer, and NRC. The physical properties of ALC, concrete, plywood, and gypsum board were analyzed. The number of physical property values found in each database is shown in Table 1. Herein, the physical property values that were duplicated in different databases were removed.

[insert Table 1.]

In Table 1, it can be seen that the total number of samples in the databases was less than 20 for any one of the physical properties; the set of physical properties for a material from the same institute was rarely complete; the number of the samples was relatively small for porosity and specific heat; and the number of samples in the databases created by IEA and Fraunhofer was relatively large.

2.2 Comparison of variability in each physical property

2.2.1 Method

The data gathered from the four databases were combined and regarded as a newly formed larger database containing the physical properties of ALC, concrete, plywood, and gypsum board. The average and standard deviation of each material's physical properties were used to evaluate the variability. The standard deviation was divided by the average to yield the relative standard deviation. For example, physical properties such as thermal conductivity and moisture permeability are correlated with density and porosity, respectively. However, in this study, the correlation between physical properties was not considered.

Outliers, values that differ significantly from other values in the databases, would strongly affect the average and standard deviation because of the small number of samples present in the databases. Therefore, such values were removed using the Smirnov-Grubbs test. In this study, the outliers were removed using a two-sided test at a significance level of 0.05 in accordance with ISO 5725–2 (Wilrich, 2010; Fridman 2012). Moreover, for physical properties that were provided as variables of humidity or moisture content, tests were conducted for each humidity or moisture content value. The moisture capacity and vapor permeability were tested for five relative humidity values (20, 40, 60, 80, and 90% relative humidity (RH)), and the thermal conductivity was tested for five moisture content values (0, 0.05, 0.1, 0.15, and 0.2kg/kg). In this procedure, data were regarded as outliers if rejected even once by the tests.

2.2.2 Result

As an example, the values of density and vapor permeability for gypsum board in databases are shown in Fig. 1. Fifteen values for density and eleven values for vapor permeability are shown.

[insert Figure 1.]

The average and standard deviation for the density and vapor permeability of the gypsum board are shown in Fig. 2 after removal of the outliers.

[insert Figure 2.]

Fig. 3 shows a comparison of the average, standard deviation, and relative standard deviation of the six physical properties for each material. In Fig. 3, the values for the moisture capacity and vapor permeability correspond to 70% RH. For the thermal conductivity, the values correspond to an equilibrium moisture content of 70% RH.

[insert Figure 3.]

As shown in Fig. 3, the magnitude of variability in basic physical quantities, such as density and porosity, and that in specific heat were relatively small, 8%, 10%, and 13% on average, respectively. However, the variability in capacity and transport properties, such as thermal conductivity and vapor permeability, were relatively large, 23%, 21%, and 37% on average, respectively. In some cases, the variability was especially large. The variability in the moisture capacity of gypsum board and in the vapor permeability of plywood reached 50%.

3. Effect of variability in physical properties on analytical results of heat and moisture transfer in a single layer wall

3.1 Method

In order to evaluate the influence that the variability in physical properties had on the analysis, the heat and moisture transfer of a single layer wall was calculated for step changes in the temperature and humidity of the surrounding air. This was done by using the average and the average plus standard deviation of the population of the physical property, which itself consisted of the data gathered from four databases as previously described.

The fluctuation in either the relative humidity or the temperature of the indoor air was used as a calculation condition for the air that was in contact with the wall. The simultaneous heat and moisture transfer equations (Matsumoto, 1978) in the hygroscopic range are shown in Table 2. In the basic equations, we assumed that the wall was homogeneous and made of non-swelling porous material and the temperature dependence and hysteresis of the equilibrium moisture content were not considered. Calculations were performed assuming the vapor permeability, moisture capacity, and thermal conductivity of the wall varied at each instance and location with the relative humidity. The surface heat and moisture transfer coefficient along with the other physical properties shown in Table 3 were used in the calculation. An overview of the analytical model is shown in Fig. 4. The solution for the periodic steady state was calculated for fluctuations in the temperature and moisture content distribution in the material over a 12 h cycle. The heat and moisture flow rate from the indoor air to the wall were output. These analytical results indicate the air conditioning load of the room, such as cooling or heating load and humidification or dehumidification load.

[insert Table 2.]

[insert Table 3.]

[insert Figure 4.]

The set of average values was compared with a set in which any one physical property value was changed from the average in order to evaluate the differences in the analytical results. This resulted in six pairs (A vs. B1, A vs. B2, …, A vs. B6) for the six kinds of physical properties, as shown in Table 4.

[insert Table 4.]

3.2 Result

In case 1 (indoor air temperature fixed at 23 °C and step changes between 80% and 60% in indoor air relative humidity), the calculated results for the physical properties of group A (control group: average values of all the physical properties were used) and those of group B (one of the physical properties was changed from the control group) were compared as shown in Fig. 5 for the surface of the material on the indoor air side. As an example, the results for the gypsum board are shown in Fig. 5, focusing on the case in which the moisture capacity was changed from the average for physical property set B. When the relative humidity of the indoor air increased, vapor flowed from the room to the wall. The absolute humidity of the surface of the material then increased (Fig. 5(a)). Simultaneously, phase change heat was generated and the temperature of the surface of the material increased (Fig. 5(c)). Vapor flow from the room to the wall (Fig. 5(b)) and heat flow from the wall to the room (Fig. 5(d)) occurred until the absolute humidity of the surface of the material was in equilibrium with the room air. As a result of increasing the moisture capacity in the set of physical properties, the fluctuation of the moisture content was reduced. Thus, the increase in absolute humidity and the decrease in vapor flow from the room to the wall became slower (Fig. 5(a), (b)). Additionally, the decrease in phase change heat and heat flow from the wall to the room were also slowed (Fig. 5(c), (d)). The differences in the vapor flow rate and heat flow rate are associated with the air conditioning load if integrated with respect to time.

[insert Figure 5.]

Hereafter, only the integrated values for the moisture and heat flow rate at the indoor wall surface during the first half of the 24 h period are shown (Fig. 5(b), (d)). This is done in order to evaluate the influence that differences between the physical property groups A and B have on the analytical result, both for case 1 (relative humidity change) and case 2 (temperature change). Fig. 6 shows the difference between the integrated values of the analytical results of the group A and B for each physical property.

[insert Figure 6.]

In terms of the density, porosity, and specific heat (Fig. 6(a), (b), (c)), the differences between the analytical results due to the variability of physical properties (difference between groups A and B) were all less than 0.3% for the four materials. In other words, the analytical results were almost identical for density, porosity, and specific heat, regardless of which physical properties were chosen from the database. The variability of these three properties thus did not affect the analytical results under the conditions adopted in this study.

As shown in Fig. 6, the change in thermal conductivity did not affect the moisture flow rate when only the indoor relative humidity was changed. Additionally, when only the indoor temperature was changed, the changes in moisture capacity and vapor permeability did not affect the heat flow rate, because the change in the amount of phase change heat generated by changes in the moisture capacity or vapor permeability was relatively small.

As shown in Fig. 6(d) and (e), the moisture flow rate under both boundary conditions and the heat flow rate in case 1 (humidity change) indicated that the integrated values of moisture and heat flow rate into a single layer wall fluctuated by approximately 10% or more. This was due to differences in the vapor permeability and moisture capacity of almost all the materials except for the moisture conductivity of gypsum board. In particular, the integrated values of moisture and heat flow rate into a single layer wall fluctuated by 20% and 40% or more due to differences in the vapor permeability of plywood shown in Fig. 3(e), and in the moisture capacity of gypsum board shown in Fig. 3(d), which had large variability. Changes in moisture content do not rapidly reach a steady state, unlike changes in temperature. Additionally, when the amount of moisture transfer changes, the rate of phase change heat generation also changes. Therefore, the analytical results were significantly affected by differences in these physical property values. The influence that the variability in the vapor permeability of gypsum board had on the analytical results was small because the average of moisture capacity was small, as shown in Fig. 3(d), and the absolute humidity at the indoor surface of the wall easily reached steady state regardless of the value of vapor permeability. However, the effect that differences in the gypsum board had on the integrated value of the heat flow rate in case 2 (temperature change) fluctuated by 5% or more, as shown in Fig. 6(e). Therefore, the effect of variability in vapor permeability and moisture capacity was significant.

As shown in Fig. 6(f), the moisture flow rate in case 2 and the heat flow rate under both boundary conditions indicated that the integrated values of moisture and heat flow rate into a single layer wall fluctuated by approximately 5% or more due to differences in the thermal conductivity of ALC and plywood. This was due to the conduction of the generated phase change heat. Because plywood has low vapor permeability and high moisture capacity, moisture accumulated on the wall surface and a large amount of phase change heat was generated. Moreover, the average of the vapor permeability and moisture capacity of concrete was similar to that of plywood. Because concrete has a very large volumetric specific heat, the analytical results were not easily affected by changes in the amount of generated phase change heat. Hence, the differences in the thermal conductivity had little effect on the analytical results. Therefore, in terms of the thermal conductivity, both the variability and the magnitude of the average of other physical properties were factors that influenced the analytical results. In particular, for materials with low vapor permeability or high moisture capacity, the differences in thermal conductivity affected the analytical results.

4. Discussion

In this study, the average value for the population collected from four databases was used as the standard for each physical property. Additionally, the standard deviation of the population was used as the physical property's representative range of variability. It should be noted that there are various methods of data collection, each of which can cause the results to differ. If variation in physical property values is considered probabilistic, the evaluation is performed using the 5th or 95th percentile values. Conversely, if a database comprises a large number of physical property values with their average values known, it is unlikely that the physical properties are randomly selected, or only extreme candidates are selected. Therefore, this study uses the "average value" and "average + standard deviation" values to demonstrate the influence of variation in the physical properties of materials. Additionally, "mean value" and "mean + standard deviation" values were used to demonstrate the influence of variation in the property values.

A stepwise change in temperature or relative humidity was used in the 1-D calculation applied in this study. If the physical properties were all constant, the model would be a linear system and the principle of superposition would be valid. The influence that variability in physical properties had on the calculations would then truly be general for various transient processes. However, some physical properties, such as vapor permeability and the sorption isotherm, are dependent on humidity, and in a strict sense, the results will differ due to the range of humidity and temperature.

The purpose of this study is to compare the magnitude of influence of the variability in physical property values of materials on analytical results, under relative humidity between 60% and 80% with normal temperature condition. The applicability of the results achieved in this study can be examined further to evaluate the phenomena that do not fall within these temperature and humidity conditions.

In this study, liquid water transfer was not considered. Instead, analysis in the hygroscopic range was focused on. The physical properties related to liquid water transfer often demonstrate strong non-linearity. Therefore, in discussing this, the conditions of the calculation should be carefully refined.

As shown in this study, the influence of variability can be derived from a combination of multiple physical properties, especially heat and moisture transfer. In other words, the “coupling” of heat and moisture should be considered in the evaluation of the influence of variability on calculated results.

In discussing the validity or reliability of the analytical model of simultaneous heat and moisture transfer, not only the equations themselves but also the physical properties included in the equations should be evaluated. The validation of the model can best be carried out by using the correct physical properties. However, it is often difficult to determine the best value for a physical property. The results of this study showed that variations in the physical properties of materials substantially influence the analytical results in certain cases. The range of variability demonstrated in the physical properties presented in this paper should be of assistance in optimizing the choice of these properties for the assessment of the model’s validity.

5. Conclusion

In this study, the physical properties related to heat and moisture transfer in porous building materials were gathered from four databases of physical properties (IEA, ASHRAE, Fraunhofer, and NRC). The variability in physical properties was analyzed for six physical properties (density, porosity, specific heat, moisture capacity, thermal conductivity, and vapor permeability) of four materials (ALC, concrete, plywood, and gypsum board) by analyzing the average and standard deviation of the population formed by the gathered data. Additionally, the influence that the variability in physical properties had on the results of numerical calculations performed using the physical properties was analyzed.

The magnitude of the variability in basic physical quantities, such as density and porosity, and that in specific heat were relatively small, on average 8%, 10%, and 13%, respectively. However, the variability in moisture capacity and transport properties, such as thermal conductivity and vapor permeability, were relatively large, on average 23%, 21%, and 37%, respectively. The moisture capacity of gypsum board and the vapor permeability of plywood reached 50%.

The influence of the variability in physical properties was evaluated based on the periodic steady-state numerical solution for the moisture and heat flow rate from a room to a wall for a single layer wall given a stepwise fluctuation with a period of 12 h in relative humidity (between 60% RH and 80% RH) or temperature (between 18 °C and 28 °C) for the indoor air side. The integrated values for moisture and heat flow rate into a single layer wall fluctuated by less than 0.3% due to differences in the density, porosity, and specific heat. However, the fluctuation reached 10% or more due to differences in the vapor permeability or moisture capacity of almost all materials. This was attributed to the change in moisture content being slower than that of temperature. This was also attributed to changes in the phase change heat generation rate due to the moisture transfer. Moreover, the fluctuation reached 5% or more due to differences in the thermal conductivity of some materials. This accounted for both the large variability and also the conduction of the phase change heat generated in materials with low vapor permeability and high moisture capacity, such as plywood. Therefore, the variability in the thermal conductivity, moisture capacity, and vapor permeability significantly affected the moisture and heat flow rate. Moreover, the influence of variability was derived not only from the variability in the physical properties but also from a combination of other physical properties, in particular heat and moisture transfer. In other words, the “coupling” of heat and moisture should be considered in the evaluation of the influence of variability on calculated results.

In simulating hygrothermal problems, one value must inevitably be chosen from the multiple potential values present in the available physical property database. Therefore, the evaluation of the range of variability and its influence on the calculated results might help to demonstrate points that should be checked in the evaluation of the simulation. In this study, the hygroscopic range was targeted. An evaluation of the high moisture content range, including liquid moisture transfer, is a necessary investigation that will be conducted as part of future work.

References

ASHRAE (2013) Chapter 26: Heat, Air, and Moisture Control in Building Assemblies—Material properties. In: *ASHRAE Handbook of Fundamentals*. Atlanta.

Barclay M, Holcroft N and Shea AD (2014) Methods to determine whole building hygrothermal performance of hemp-lime buildings. *Building and Environment* 80: 204–212.

Defraeye T, Blocken B and Carmeliet J (2013) Influence of uncertainty in heat–moisture transport properties on convective drying of porous materials by numerical modelling. *Chemical Engineering Research and Design* 91: 36–42

Feng C, Guimarães AS, Ramos N, et al. (2020) Hygric properties of porous building materials (VI): a round robin campaign. *Building and Environment* 185: 107242

Feng C and Janssen H (2016) Hygric properties of porous building materials (II): Analysis of temperature influence. *Building and Environment* 99: 107–118

Feng C, Janssen H, Feng Y, et al. (2015) Hygric properties of porous building materials: Analysis of measurement repeatability and reproducibility. *Building and Environment* 85: 160–172

Feng C, Janssen H, Wu C, et al. (2013) Validating various measures to accelerate the static gravimetric sorption isotherm determination. *Building and Environment* 69: 64–71.

Fraunhofer Institute for Building Physics (2018) WUFI. Available at: http://wufi.de/en/ (accessed 12 Jan. 2021).

Fridman AE (2012) Chapter 8 Assurance of Measurement Accuracy in Compliance with ISO 5725 Standards. In: *The Quality of Measurements: A Metrological Reference*. Springer, 179–195

Hens H (2007) Modeling the heat, air, and moisture response of building envelopes: what material properties are needed, how trustful are the predictions? *Journal of ASTM International* 4: 1–11.

Janssen H (2013) Monte-Carlo based uncertainty analysis: sampling efficiency and sampling convergence. *Reliability Engineering and System Safety* 109: 123–132

Janssen H, Blocken B, Roels S, et al. (2007) Wind-driven rain as a boundary condition for HAM simulations: analysis of simplified modelling approaches. *Building and Environment* 42: 1555–1567.

Kumaran K (1996) Heat, air and moisture transfer through new and retrofitted insulated envelope parts, Final Report Volume 3 Task 3: Material properties. *IEA ANNEX 24 HAMTIE.*

Kumaran K (2002) A thermal and moisture transport property database for common building and insulating materials. *Final report from ASHRAE Research Project 1018-RP.*

Kumaran K, Lackey J, Normandin N, et al. (2002) Summary report from Task 3 of MEWS Project at the Institute for Research in Construction – Hygrothermal properties of several building materials. *IRC-RR-110, National Research Council Canada.*

Kunzel HM (1995) Simultaneous Heat and Moisture Transport in Building Components—One- and Two-dimensional Calculation using Simple Parameters. *IRB Verlag.*

Matsumoto M (1978) Simultaneous heat and moisture transfer in porous wall and analysis of internal condensation. In: Hoogendoorn C and Afgan NH (eds) *Energy Conservation in Heating, Cooling, and Ventilating Buildings* 1. Hemisphere Publishing Corporation, 45–58

Nishimura H, Kominami K and Kobayakawa K (2004) An estimation of the uncertainty of measurement on thermal insulation test. *Journal of Environmental Engineering, Architectural Institute of Japan* 584: 17–23 (in Japanese, with English abstract)

Pietrak K, Kubiś M, Cieślikiewicz Ł, et al. (2019) Measurement of thermal, hygric and physical properties of bricks and mortar common for the Polish market. *IOP Conference Series: Materials Science and Engineering* 660: 012022.

Prada A, Cappelletti F, Baggio P, et al. (2014) On the effect of material uncertainties in envelope heat transfer simulations. *Energy and Buildings* 71: 53–60

Roels S (2008) Whole building heat, air and moisture response, Subtask 2: Experimental Analysis of Moisture Buffering, *IEA ANNEX 41.*

Roels S, Carmeliet J, Hens H, et al. (2003) Moisture Transfer Properties and Materials Characterisation. *HAMSTAD Work Package 1 Final Report*.

Roels S, Carmeliet J, Hens H, et al. (2004) Interlaboratory comparison of hygric properties of porous building materials, *Journal of Thermal Envelope and Building Science* 27: 307–325

Wilrich P (2010) The determination of precision of qualitative measurement methods by interlaboratory experiments. *Accreditation and Quality Assurance* 15: 439–444

Xi Y, Bazant ZP, Molina L, et al. (1994) Moisture diffusion in cementitious materials—Moisture capacity and diffusivity. *Advanced Cement Based Materials* 1: 258–266

Table 1. The number of hygrothermal property data in the hygroscopic range stored in the database of each organization.

		Density	Porosity	Specific heat	Moisture capacity	Vapor permeability	Thermal conductivity
IEA	ALC	10	1	3	4	4	6
	Concrete	5	1	2	7	8	4
	Plywood	6	0	1	4	6	3
	Gypsum Board	9	1	1	3	4	3
ASHRAE	ALC	1	0	0	1	1	0
	Concrete	1	0	0	1	1	0
	Plywood	4	0	1	4	4	6
	Gypsum Board	1	0	1	1	2	1
Fraunhofer	ALC	4	2	2	4	4	4
	Concrete	7	7	3	7	7	4
	Plywood	5	5	5	5	5	5
	Gypsum Board	4	4	4	4	4	4
NRC	ALC	1	0	1	1	1	1
	Concrete	1	0	1	1	1	1
	Plywood	1	0	0	1	1	1
	Gypsum Board	1	0	1	0	1	1
Total	**ALC**	**16**	**3**	**6**	**10**	**10**	**11**
	Concrete	**14**	**8**	**6**	**16**	**17**	**9**
	Plywood	**16**	**5**	**7**	**14**	**16**	**15**
	Gypsum Board	**15**	**5**	**7**	**8**	**11**	**9**

Concretes with different water-cement ratios were assessed as different materials in this table.

Table 2. Simultaneous heat and moisture transfer equations in porous materials in the hygroscopic range.

heat balance equation	$C\rho \frac{\partial \theta}{\partial t} = \nabla(\lambda \nabla \theta) - LW$	(1)
water vapor balance equation	$\Phi\rho' \frac{\partial X}{\partial t} = \nabla(\lambda' \nabla X) + W$	(2)
liquid water balance equation	$\frac{\partial w}{\partial t} = \nabla(D_{wl} \nabla w + D_{\theta l} \nabla \theta) - W$	(3)
heat balance equation (By substituting (2) into (1))	$C\rho \frac{\partial \theta}{\partial t} = \nabla(\lambda \nabla \theta) + L(\nabla(\lambda' \nabla X) - \Phi\rho' \frac{\partial X}{\partial t})$	(4)
moisture balance equation (By substituting (2) into (3))	$\frac{\partial w}{\partial t} = \nabla(\lambda' \nabla X) - \Phi\rho' \frac{\partial X}{\partial t}$	(5)
Equilibrium relationship (Sorption isotherm)	$X = g(w, \theta)$	(6)
heat boundary condition	$[-\lambda \nabla \theta]_s = \alpha(\theta_a - \theta_s) - L\alpha'(X_a - X_s)$	(7)
moisture boundary condition	$[-\lambda' \nabla X]_s = \alpha'(X_a - X_s)$	(8)

where θ is the temperature [K], X is the absolute humidity [kg/kg(DA)], w is the moisture content [kg/m^3], t is the time [s], λ is the thermal conductivity [W/(m・K)], λ' is the vapor permeability [kg/(m・s・(kg/kg(DA)))], D_{wl} is the moisture diffusion coefficient for the moisture content gradient [m^2/s], $D_{\theta l}$ is the moisture diffusion coefficient for the temperature gradient [kg/(m・s・K)], C is the specific heat [J/(kg・K)], ρ is the density of material [kg/m^3], L is the latent heat of evaporation [J/kg], W is the amount of water evaporation in the pores [kg/(m^3・s)], Φ is the porosity [m^3/m^3], ρ' is the density of the dry air [kg/m^3], α is the combined heat transfer coefficient at the surface of the material [W/(m^2・K)], and α' is the moisture transfer coefficient at the surface of the material [kg/(m^2・s・(kg/kg(DA)))]. The subscripts "a" and "s" signify 'air' and 'surface of material', respectively. In the hygroscopic range, liquid water transfer can be ignored; thus, $D_{wl} = 0$ and $D_{\theta l} = 0$.

Table 3. Surface heat and moisture transfer coefficient along with other values used in the calculation.

Combined heat transfer coefficient (Indoor side)	9.3[W/(m^2・K)]
Combined heat transfer coefficient (Outdoor side)	23.2[W/(m^2・K)]
Moisture transfer coefficient (Indoor side)	4.4[g/(m^2・s・(kg/kg(DA)))]
Density of dry air	1.2[kg/m^3]
Latent heat of water	2454.2[kJ/kg]

Table 4. Seven types of physical property values sets used to analyze the effect that differences in physical property values have on the analytical results.

<table>
<tr><th colspan="3"></th><th>Density</th><th>Porosity</th><th>Specific heat</th><th>Moisture capacity</th><th>Vapor permeability</th><th>Thermal conductivity</th></tr>
<tr><td rowspan="7">Physical property values sets</td><td colspan="2">A (Control)</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td></tr>
<tr><td rowspan="6">B</td><td>B_1</td><td>Avg.+SD</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td></tr>
<tr><td>B_2</td><td>Avg.</td><td>Avg.+SD</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td></tr>
<tr><td>B_3</td><td>Avg.</td><td>Avg.</td><td>Avg.+SD</td><td>Avg.</td><td>Avg.</td><td>Avg.</td></tr>
<tr><td>B_4</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.+SD</td><td>Avg.</td><td>Avg.</td></tr>
<tr><td>B_5</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.+SD</td><td>Avg.</td></tr>
<tr><td>B_6</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.</td><td>Avg.+SD</td></tr>
</table>

The average values of the data population are provided as a control (Group A). Either one of the physical properties were changed from the control (Group B). In Group B, one of the physical properties was given as an average plus the standard deviation of the data population.

(a) (b)

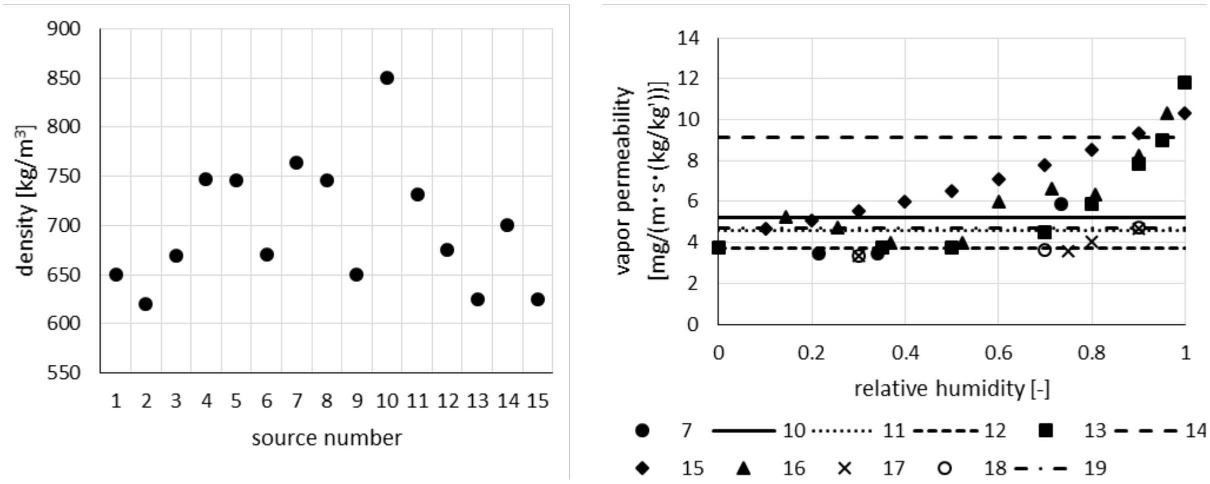


Figure 1. Measurement results for the (a) density and (b) vapor permeability of gypsum board from each data source.

For vapor permeability, the data associated with unclear measurement conditions of relative humidity are shown as a line. Each data source was numbered to distinguish them and the same number was assigned to sources that showed both density and vapor permeability.

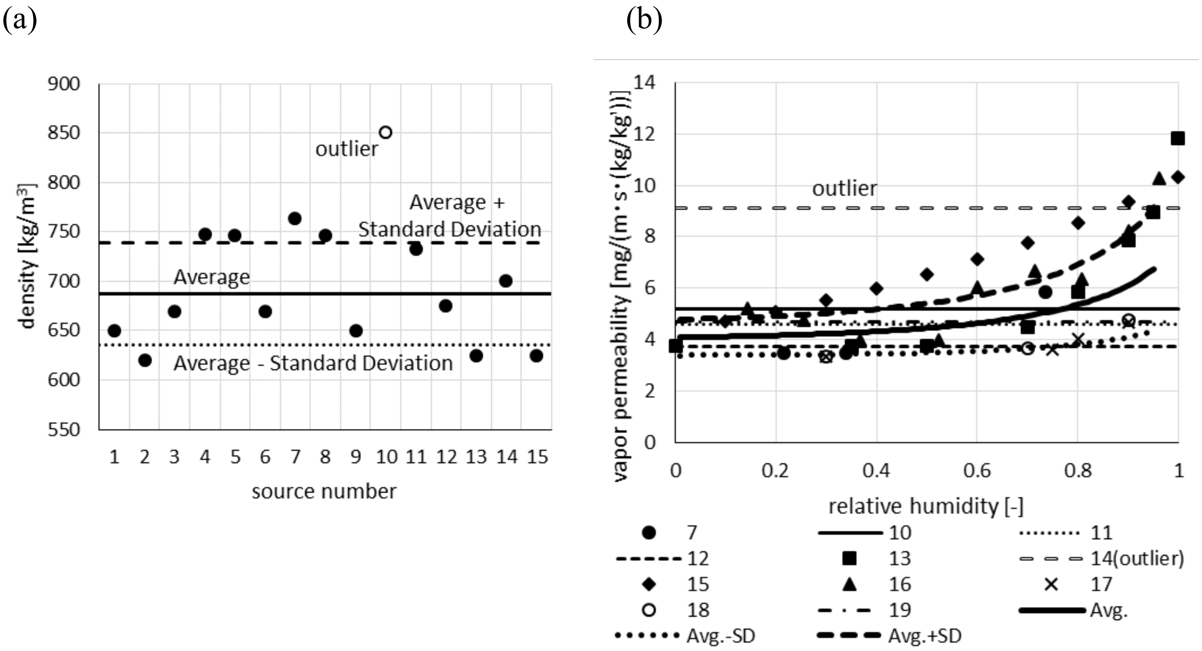


Figure 2. Average and standard deviation of the (a) density and (b) vapor permeability of gypsum board excluding outliers.

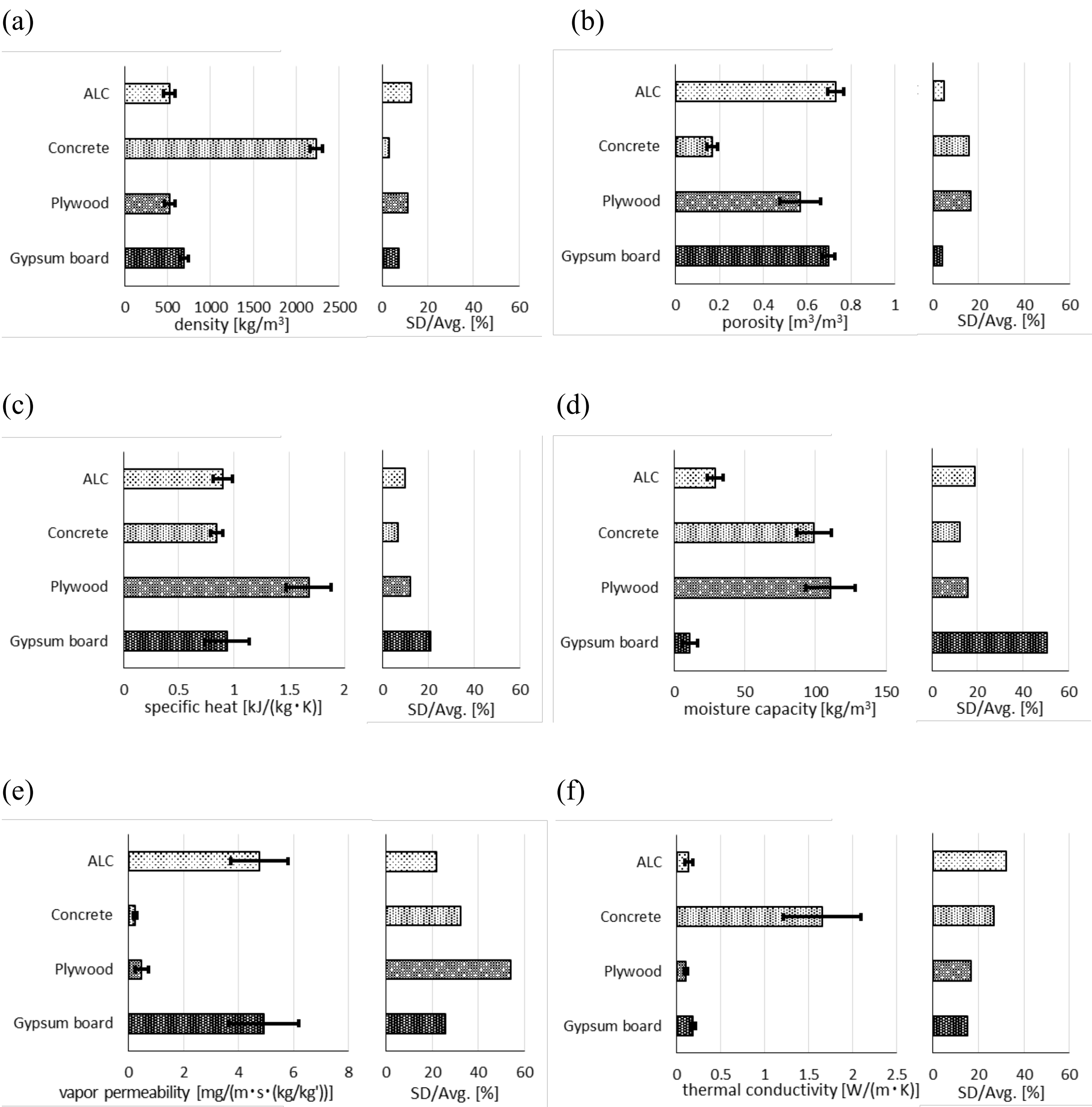


Figure 3. Average, standard deviation, and relative standard deviation of (a) density, (b) porosity, (c) specific heat, (d) moisture capacity, (e) vapor permeability, and (f) thermal conductivity of ALC, concrete, plywood, and gypsum board.

On the left-hand side, the bar graph and the error bar show the average and the standard deviation, respectively. On the right-hand side, the bar graph shows the relative standard deviation. Although the changes based on the relative humidity in vapor permeability, moisture capacity, and thermal conductivity were considered in this study, those values at 70% relative humidity are shown in this figure.

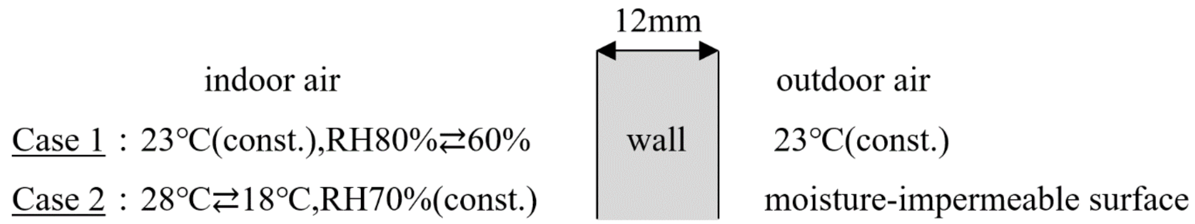


Figure 4. Boundary conditions for both sides of a single layer wall.

Changes in the relative humidity or the temperature of the indoor air over a period of 12 h were used for the indoor side. Temperature was kept constant on the outdoor side with moisture-impermeable conditions for moisture transfer.

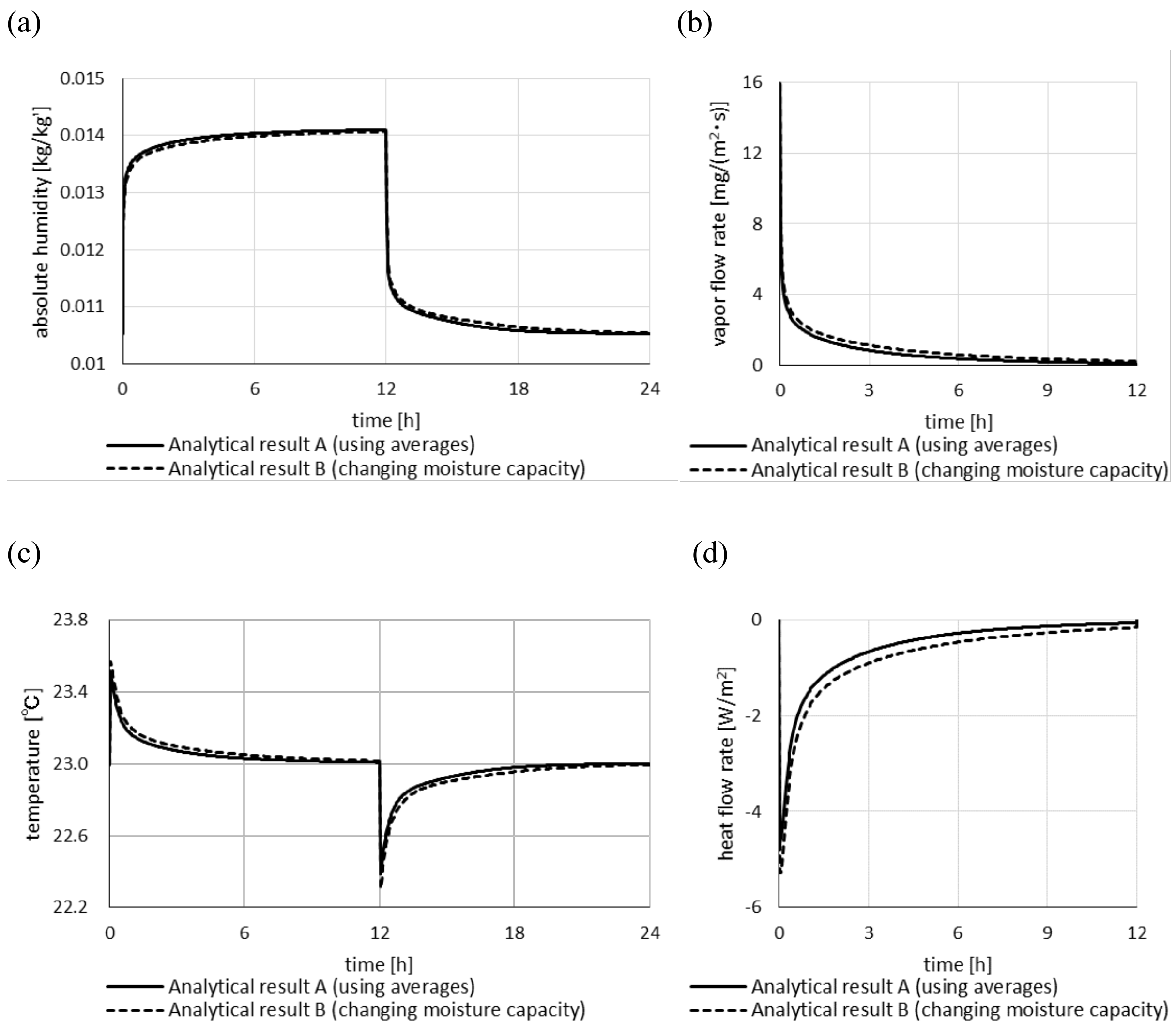
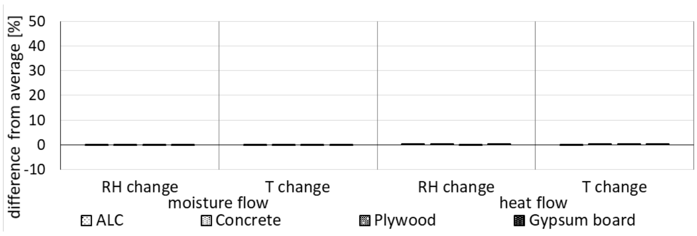
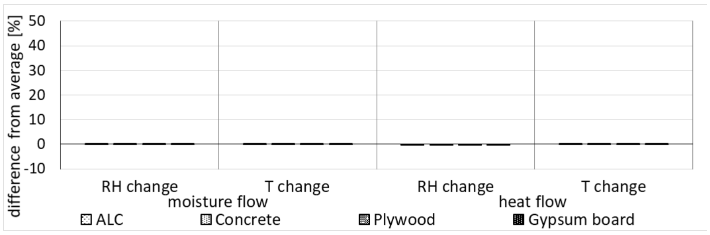


Figure 5. Comparison between the results for the control group (Group A) and those for one of the groups after changing one of the physical properties (Group B). Only the Group B_4 results for gypsum board are shown. (a) Absolute humidity on the surface of the wall on the indoor air side, (b) moisture flow rate from indoor air to the wall, (c) temperature on the surface of the wall on the indoor air side, and (d) heat flow from the indoor air to the wall.

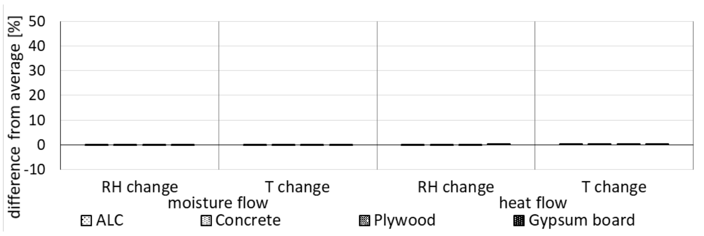
(a) Density (Difference between group A and group B_1)



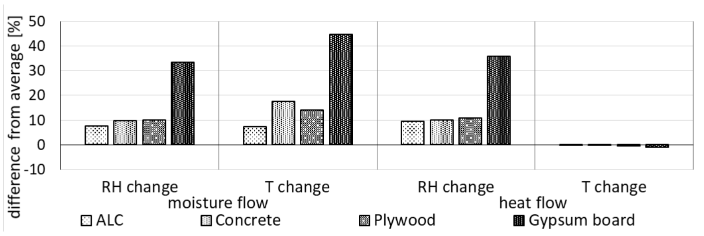
(b) Porosity (Difference between group A and group B_2)



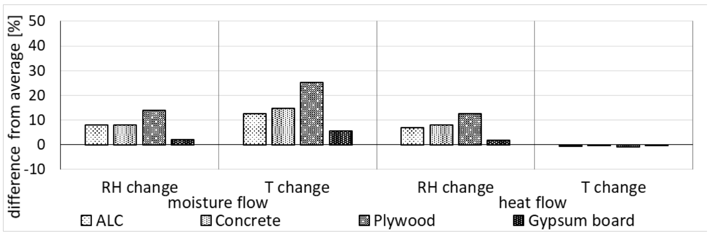
(c) Specific heat (Difference between group A and group B_3)



(d) Moisture capacity (Difference between group A and group B_4)



(e) Vapor permeability (Difference between group A and group B_5)



(f) Thermal conductivity (Difference between group A and group B_6)

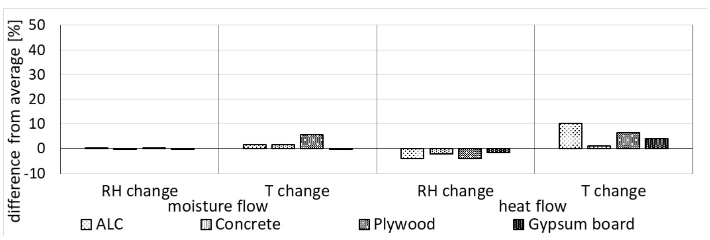


Figure 6. Differences between the integrated moisture and heat flow due to variability in the six physical properties ((a) to (f)) of four materials based on the difference between group A and either one of groups B_1, B_2,…, B_6 for both case 1 (RH change) and case 2 (T change).