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Møller, Eva B.; Hansen, Ernst Jan de Place; Brandt, Erik; Kielsgaard Hansen, Kurt

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Moisture assessment by fast and non-destructive in- situ measurements

Eva B. Møller, Ph.D. ¹

Ernst Jan de Place Hansen, Ph.D. ¹

Erik Brandt, M.Sc. ¹

Kurt Kielsgaard Hansen, Associate Professor, Ph.D. ²

¹ Danish Building Research Institute/Aalborg University Copenhagen, Denmark

² Technical University of Denmark, Denmark

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SUMMARY:

A building inspection report is made in connection with the resale of 90% of all single-family houses in Denmark. The building inspection is visual with the option of using simple hand-held instruments but with no destructive measures allowed. However, many construction components have a high moisture content, which is not revealed by this inspection. The moisture content may become a problem for the buyers. This problem might have been avoided if the moisture content of the building materials was measured on inspection. This is easily done in wood-based materials but for example in concrete and brick the moisture content is difficult to determine within a short period time. There is political pressure to include moisture measurements in the report if it does not increase the cost of the inspection significantly.

Therefore, a moisture-measuring method is needed that is non-destructive, fast to use, easily applicable and suitable for most porous building materials. Furthermore, the measurements must be reliable at the high end of the hygroscopic area and describe absolute moisture content or corresponding relative humidity. The existing methods for moisture measuring cannot meet these requirements, and those who come close are very expensive. This paper describes a method under development; with simple means and within a few hours, the method can measure the absolute moisture content or the corresponding relative humidity in constructions in a non-destructive way. The method is based on measurements of the relative humidity of the air in a small hood placed tightly and sealed to the surface of the construction. Results with aerated concrete covered with acrylic paint are presented.

1. Introduction

In Denmark a building inspection report is made by a certified building inspector at more than 90% of all resales of single-family houses. The report points out building components that are in worse condition than is to be expected in a well-maintained house of the same age and style. The building inspection report has two purposes:

- To point out weaknesses of the house to potential buyers (consumer guidance)
- Form the basis for an insurance that exempts the seller from his 10-year period of liability for hidden building damages and defects. The buyer will have insurance against hidden building damages and defects. The cost of the insurance is split evenly between seller and buyer.

The insurance companies may exclude building components mentioned in the inspection report.

It is only possible to take out this insurance if there is a building inspection report made by a certified building inspector and reported to a central secretariat. The arrangement is administered by the Danish Ministry of Housing, Urban and Rural Affairs.

The building inspection is visual with the option of using simple hand-held instruments but no destructive measures are allowed. The inspection includes all kinds of damages and defects; however, the experience is that one of the major problems is that some construction components have a high moisture content, which is not revealed by this inspection. The moisture may become a problem for the buyers. The problem could have been avoided if the moisture content of the building materials was measured on inspection. This is easily done in wood-based materials but e.g. in concrete and brick the moisture content is difficult to determine within a short period of time. There is political pressure to include moisture measurements in the report if it does not increase the cost of the inspection significantly.

Measuring relative humidity in indoor air would only provide information on the hygrothermal conditions in that specific moment. By extra airing and heating of the house before the inspection takes place, the result can easily be manipulated to give the impression of less humidity than would have been the case under normal conditions. However, materials act relatively slowly within a short period of airing and heating, and they therefore represent the memory of the house; if materials in general are moist, it would take a long time to reduce the moisture content simply by airing and heating. Depending on the reasons for moist materials, it is not possible in this way to reduce the moisture content in materials significantly.

Therefore, a moisture-measuring method is needed that should be non-destructive, fast to use, easily applicable and suitable for most porous building materials. Furthermore, the measurements must be reliable at the high end of the hygroscopic area and describe absolute moisture content or the corresponding relative humidity (RH). The existing methods for moisture measuring cannot meet this requirement, and those that come close are very expensive.

This paper describes a method under development that meets the above criteria. The method is based on measurements of the relative humidity of the air under a small hood placed tightly and sealed to the surface of the construction. The first experiments were conducted and described in Andersen & El-Khattam (2012). The experiments described in this article concentrated on how the method could be used in inorganic porous building materials covered by acrylic paint, a common surface treatment with a relatively high vapour resistance.

2. Methods for measuring moisture in materials and air

2.1 Existing methods

There are several instruments available for moisture measurements; some are destructive some are not, some measure relative humidity, some measure the moisture content in materials. The accuracy of the measurements varies considerably and so does the use of different methods and instruments. The methods described in the following are all used in practice, mainly for non-destructive in-situ measurements. Other methods are available but these are either expensive and therefore not commonly used or mostly used in laboratories.

2.1.1 Accurate measurements

The most accurate way to determine moisture content in materials is, in brief, to collect a sample of the material, weigh it, dry it at 103-105 °C until the weight is stable and determine the weight of the dry material. The water content can then be determined as the difference of the weight before and after the drying divided by the dry weight.

This method is accurate but destructive, takes time and is not suitable for in-situ measurements.

2.1.2 *Absolute measurements in materials*

An effective way to determine the absolute moisture content of timber is by measuring the electrical resistance between two pins pressed into the timber. This method is almost non-destructive; it only leaves two pinholes which may disappear after some time. Most timber is made of pine or spruce and therefore many instruments with two pins directly convert the resistance to moisture content in weigh-% for pine or spruce, but ideally the instrument or the scale must be calibrated to the actual wood species.

The moisture content in other materials could theoretically be measured in the same way if properly calibrated. However, in most other materials, e.g. gypsum, it is difficult to ensure that there is no slip between the material and each pin; slips influence the measurement.

Most other moisture measurements are relative; the absolute moisture content can only be determined if an absolute scale is established by a destructive measuring of the absolute moisture content in a few points and by correlating this to the scale.

2.1.3 *Relative measurements in materials*

There is a variety of methods for determining how the moisture content in a material varies relatively. This is practical when the moistest areas are to be identified. However, it does not determine the absolute moisture level. The methods are used on porous materials, where different properties depend on the moisture content. The techniques used in practice include measuring impedance, capacitance, dielectricity, hydrogen content and temperature (Phillipson et al. 2007).

Most of these methods are non-destructive and measures conditions on or near the surface.

2.1.4 *Relative humidity*

Moisture in air can be measured in different ways ranging from traditional mechanical hygrometers where humidity determines the expansion and contraction of a specific material, over methods using the dew point temperature (chilled mirror hygrometer) or wet and dry temperature (wet and dry bulb psychrometer) to different optical methods and methods of measuring dielectric changes in a thin hygroscopic film. More thorough descriptions are for example given in Yeo et al. (2008).

2.2 Relative humidity or moisture content in materials

Sorption curves connect moisture content in materials with relative humidity, however, there are many sorption curves within the same material type. Hansen (1986) compiled sorption curves for the most common building materials and the collection contains five sorption curves for aerated concrete alone, illustrating that it is not enough to know the material type, as the sorption curve for the specific material must be known to determine the absolute moisture content from the relative humidity and vice versa.

The main concern about moisture is the risk of deterioration of materials and mould growth. For wood-based materials the moisture limits are normally given as weigh-% of wood (e.g. 20 weigh-% for deterioration and 16 weigh-% for mould growth) as well as humidity (85% RH and 75% RH respectively), but for other materials the limits are less clear. Deterioration is mainly a concern in wood-based materials and metals. This paper does not deal with corrosion and metals are therefore not treated. Mould growth can appear at a lower moisture level than deterioration, and on all surfaces, so therefore limits for mould growth should be used to determine whether the moisture levels in a building element are too high.

Mould grow on surfaces and limits for mould growth depend on the material and the degree of contamination, as mould live on organic material including what might be available in dust and dirt. The simplest way to describe the risk of mould growth is to describe the relative humidity on the

surface of a building element without discriminating between different materials. The method might be too simple with a risk of overestimating the risk of mould growth on inorganic, relatively clean surfaces or underestimating the risk on diffusion-open organic surfaces e.g. wallpaper with sawdust. However, it may be sufficient for fast determination of whether the moisture level is elevated or not.

2.3 New near-surface measurement

Sometimes practitioners make a simple assessment of moisture transport through a building component by covering e.g. 0.5-1.0 m² of a surface with plastic foil for a few days; if there is condensation in the area covered by plastic, moisture is transported to the surface. A more standardised method is described in ASTM (2013), where moisture content in concrete floors is determined by placing a hood on the clean floor, sealing it to the surface and after 72 hours the relative humidity under the hood describes how moist the concrete is. Most flooring and surface treatments cannot be applied if the concrete is too moist and most manufacturers describe this upper limit for moisture in floors by the relative humidity.

This project was inspired by these simple methods; the hypothesis was:

It is possible to measure the near-surface moisture in the material by placing and sealing a hood tightly to the surface. After 1-2 hours the relative humidity under the hood is similar to the relative humidity in the surface-near pores in the material.

If this hypothesis is true, the method could be used as a non-destructive way to determine the moisture content in the materials in existing houses. The result would be given as the relative humidity close to the surface, which would be sufficient, as the reasons for making these measurements is to determine whether the moisture content is acceptable in terms of risk of mould growth.

3. Previous findings

Initial experiments were conducted by Andersen and El-Khattam (2012); their research was mostly conducted on aerated concrete. They developed a “moisture hood” to be placed on the surface of the material of which the moisture content was to be measured. A sensor, measuring temperature and relative humidity was placed inside the box. In brief, their findings were:

- *Design of the hood.* Experiments were initially conducted with an aluminium hood (80 mm diameter, 50 mm high), later smaller hoods were used; the smallest and simplest was fastening the temperature and humidity sensor to the surface with aluminium tape. The different hoods were tested with and without thermal insulation. The conclusion was that the results of the measurements were not affected by the volume of the hood. Furthermore, thermal insulation had no effect.
- *Sealing to the surface.* To avoid the influence of the relative humidity in the surrounding air, the hood itself must be vapour tight. The sealing between edge of the hood and the surface of the material must also be tight and at the same time removable to ensure that the method is non-destructive. The aluminium tape was not easy to remove, however, reusable adhesive gum, which is normally used for pasting e.g. drawings on painted walls, was found to be easy to place and remove, the gum itself had a vapour resistance (Z-value) of $233 \cdot 10^9$ Pa·m²·s/kg at a thickness of 3.5 mm. This was considered to be sufficiently vapour tight.
- *Tightness of the surface, depth of measurement and time to equilibrium.* The hood was tested on aerated concrete with different surface treatments. The Z-value of the treatments varied from $0.09 \cdot 10^9$ and $1.58 \cdot 10^9$ Pa·m²·s/kg (two layers of silicate and acrylic paint, respectively). The specimens were conditioned at 85% RH and sealed at all sides except the painted side. The specimens were left to dry and had dried from one side for 9-14 days at 65% RH. Sensors were placed in drilled holes in different depths to determine a moisture profile. Apparently the surface treatment had an influence on the drying of the specimens and on the relative humidity under the hood. The relative humidity under the hood placed on silicate paint (low vapour

resistance) became constant after approximately 10 hours; the relative humidity corresponded to the relative humidity at a depth of 15 mm. When placed on acrylic paint, the relative humidity under the hood was also constant after 10 hours but at a lower level than 15 mm inside the material, probably corresponding to the moisture level on the surface.

4. Materials and methods

Based on the findings of Andersen and El-Khattam (2012) it was decided to investigate whether the “moisture hood” could be modified making it possible to determine the relative humidity of an inorganic building material immediately behind a layer of acrylic paint. As neither the thermal insulation nor the volume of the hood seemed to have any influence, the experiments were conducted without thermal insulation and with a hood size that fitted the size of a wireless sensor.

4.1 Building materials and equipment

Emphasis was put on using materials and surface treatments that are commonly used in the Danish building stock and equipment that is commercially available and suitable for measurements in the field.

4.1.1 Building materials and surface treatments

Typical inorganic building materials were used as materials, the moisture content of which was to be determined. The specific materials are listed in Table 1.

Table 1. Building materials used in most experiments. Values are average values determined by simple weighing and distance measurements.

	Concrete	Aerated concrete	Brick
Density	2200 kg/m ³	535 kg/m ³	1830 kg/m ³
Size	400 x 400 x 50 mm	600 x 400 x 50 mm	230 x 110 x 55 mm

One side of all specimens was given a surface treatment of one layer of putty (less than 0.5 mm thick) and one layer of liquid primer with a viscosity like water as well as two layers of acrylic paint. It was the same type of paint as used by Andersen and El-Khattam (2012), e.g. the Z-value of the surface treatment was $1.58 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}$.

4.1.2 Materials for moisture measuring device

The hood consisted of an aluminium hood (diameter 85 mm, height 15 mm), sealed to the surface with reusable adhesive gum (Z-value = $233 \cdot 10^9 \text{ Pa} \cdot \text{m}^2 \cdot \text{s}/\text{kg}$ at a thickness of 3.5 mm). A wireless sensor (ClimaSpot) was placed under the hood. All sensors were new and therefore calibrated.

4.2 Methods

Modification of the method involved one small destructive measure; the surface was penetrated by a nail (3 mm in diameter). The idea was that air and thereby moisture from the pores in the aerated concrete behind the acrylic paint would be transported into the hood much faster than if it could be transported only through the relatively tight acrylic paint. As the number of holes could be important, the theory was tested with different numbers of penetrations of the surface treatment under the hood. Furthermore, the effect of a small negative pressure under the hood was investigated. Consequently, the following parameters were investigated:

- Number of penetrations: 1, 2 and 3
- Pressure difference under the hood: 0 and -0.5 atm
- Three different building materials
- Conditioning of the building material prior to testing: $90\% \pm 5\%$ RH and $65\% \pm 3\%$ RH

Each experiment was repeated twice reaching a total of 108 experiments.

The procedure was always the same:

- After applying the surface treatment, the specimens were conditioned in a climate chamber with the prescribed relative humidity at 22 ± 2 °C until the weight was constant.
- Each specimen was wrapped in 0.2 mm PE-foil. Only the painted side was left unsealed
- The penetrations were made by a nail
- The specimen was placed in a climate chamber at $50\% \pm 3\%$ RH and $22^\circ\text{C} \pm 2$ °C.
- The hood including sensor and possibly suction device was sealed to the treated surface.
- Temperature and relative humidity under the hood were registered every 4 minutes for more than 50 hours.

The set-up is shown in Figure 1.



Figure 1. Experimental set-up showing moisture hoods sealed at the edge to the surface of bricks wrapped in PE-foil. Two experiments are conducted at the same time; one with under pressure (with suction device) and one without pressure difference.

5. Results and discussion

The project included many experiments and only selected data representative of the experiments are shown in this paper. Figure 2 shows the results for aerated concrete for the first 12 hours of the experiments. After this time, changes were very small. Concrete and brick show similar results.

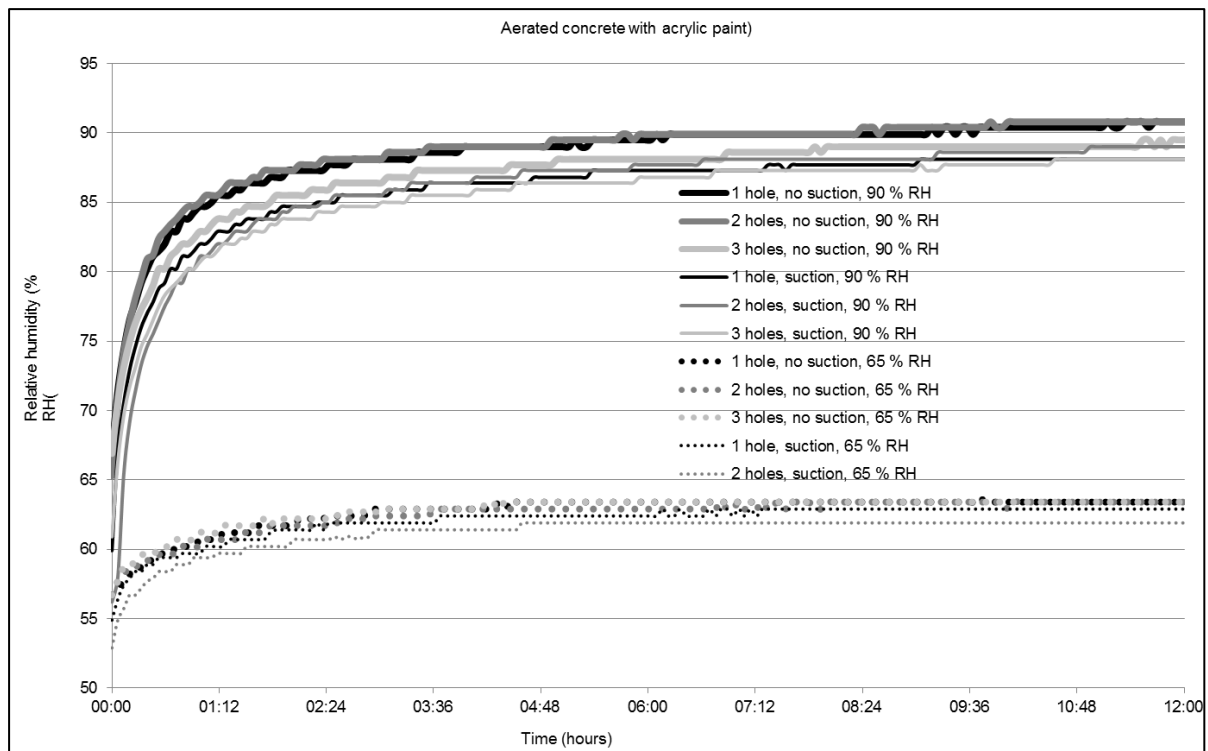


Figure 2. Results for aerated concrete, time (hours vs. RH). Measurements with 3 holes and suction at 65 % RH are missing. Concrete and brick show similar results.

The relative humidity under the hood in some of the experiments with suction (not shown here) stayed at a level similar to the relative humidity in the room. Apparently the leakage was too significant to measure the moisture from the building material. In one case, the relative humidity started at a low level but after approximately one day it went up to the expected level. Maybe the suction had tightened the sealing after some time.

Experiments without suction did not show these unexpected results but were more stable. Consequently, suction did not seem to improve the method. On contrary; measurements without suction reacted faster and were more close to the expected value than when suction was used. Moreover, establishing controlled suction might be difficult in the field. Therefore, suction should be omitted.

5.1 Penetrations

Apparently the number of penetrations did not affect the readings; there was no difference whether there was one or three holes. The number of penetrations should therefore be kept to a minimum, as this modification of the method was destructive, although the holes were very small.

5.2 Time to equilibrium

There is a clear difference in the readings in Figure 2 between the specimens conditioned at $90\% \pm 5\%$ RH and at $65\% \pm 3\%$ RH. The difference showed almost instantly. Therefore, the method would be fast for relative measurements. However, the aim is to find the absolute moisture content or the corresponding relative humidity. Apparently the measurements became stable after approximately 5 hours. For the purpose of this method, this was too long.

However, after 1 hour 30 minutes the measurements showed a clear tendency of what to expect; in Figure 2, the specimens conditioned at 90% RH and 65% RH had reached 90% and 80%, respectively, of the total rise in relative humidity. If the method should be used as planned, it must be evaluated

whether it is possible to create a tendency line and from this estimate the final rise. This should be evaluated together with results from measurements on surfaces covered by silicate paint or with no paint, to see whether it is possible to use the method independently of the surface treatment.

5.3 Surface or in-depth measurements

For silicate paint it was possible to measure the relative humidity 15 mm inside aerated concrete after leaving the hood on the surface for 10 hours. With a single penetration of an acrylic paint, the relative humidity immediately behind the paint, could be directly determined after 5 hours. The main concern of the buyer of a house is whether there is a risk of mould growth or not; as mould growth occurs at the surface it might be sufficient to determine the moisture level immediately behind the paint or at the surface itself.

As surface measurements are very uncertain, measurements immediately behind the paint may be more reliable; if the moisture level is high, it is a reasonable assumption that the risk of mould growth is high. It is therefore sufficient to determine the relative humidity immediately behind the paint.

6. Conclusion

The experiments showed that it is possible to measure the near-surface moisture in the material by placing a tightly sealed hood on the surface and measure the relative humidity in the box. However, if the material had a surface treatment of acrylic paint, it took approximately 5 hours until equilibrium was reached if the surface had a small penetration under the hood. For the purpose of doing non-destructive in-situ measurements within 1-2 hours, the results must be extrapolated by creating a tendency line based on early measurements as this will increase the uncertainty of the final result.

There is no need for establishing suction under the hood; the risk of sucking air from the room instead of air from the pores in the material is too high, as the sealing between hood and surface becomes very critical. At the same time, only one small penetration of the paint is needed, as more penetrations will neither enhance the precision of the measurement nor shorten the time to equilibrium.

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