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DIRECT MEASUREMENT OF MOISTURE INGRESS IN PV LAMINATES

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ABSTRACT: This work demonstrates a novel method for the measurement of moisture ingress into PV laminates, by the use of humidity indicator cards encapsulated within the structure. The humidity indicator cards change colour due to moisture exposure, which is quantified by processing images of the samples taken with a camera. To allow the variance of colour to be matched to specific levels of humidity, a detailed calibration was first performed. To achieve this, laminates with the structure [EVA-humidity indicator card-EVA-glass] were stabilised in an environmental chamber at 85°C at increasing levels of relative humidity. The colour change of the humidity indicator cards corresponding to the relative humidity inside the chamber was then plotted on RGB colour space diagrams. The purpose of this work is the development of a measurement method for the moisture that accumulates at the front side of PV cells, for the experimental verification of simulations of the moisture ingress into PV modules and the better understanding of degradation modes related to corrosion.

Keywords: reliability, polymer film, spectroscopy, moisture ingress

1 INTRODUCTION

PV modules that are installed in the field are exposed to various environmental conditions. The combination of different environmental factors stresses them, causing different types of performance degradation and, ultimately, failures [1]. One of the most important environmental factors is moisture ingress, which causes degradation of the PV modules because of chemical reactions with the polymers that are used in the PV laminate (back sheet, encapsulant) and the metallic components of the PV cells [2]. In the case of ethylene vinyl acetate (EVA) encapsulants, moisture can react at elevated temperatures with the VA content, forming acetic acid which then reacts with the metallic components of the cells, causing corrosion [3].

As moisture ingress plays such a crucial role in the degradation of a PV module, the measurement and the prediction of it is very important. A theoretical model based on Finite Element Analysis (FEA) for the prediction of the moisture content is very well established, but not evaluated thoroughly for structures that include cells. Kempe [4] modelled the moisture ingress in PV modules exposed to conditions typical of different locations such as Miami, Golden and Phoenix. Hulsmann and Weiss [5] simulated, using COMSOL Multiphysics, the moisture ingress in PV modules aged according to the damp-heat test of the IEC 61215 standard, and in four different climatic locations.

Some experimental evaluation of moisture ingress has been performed on laminates, either with or without PV cells present. Jankovec et al. [6] and Slapsak et al. [7] measured the moisture ingress in PV laminates of different structures by embedding digital humidity sensors in the stacks. Carlsson et al. [8] measured the moisture ingress in glass-polymer structures by encapsulating TiO₂ films on glass substrates, a method incompatible with solar cells. Another humidity sensor was manufactured by Kempe et al. [9] by encapsulating Ca films in glass-glass laminates, which can qualify the absence or presence of moisture, but not quantify the level. Finally, Kapur et al. [10] have measured the moisture ingress in glass-glass laminates by using Fourier Transform Infrared (FTIR) spectroscopy.

The purpose of the work reported in this paper is the development of a novel moisture measurement method, which involves encapsulation of humidity indicator cards in PV modules. With this method, the humidity level present at the front side of the PV cells can be quantified, and could also be applied to other locations in the devices where line-of-sight to the indicator cards is available. The proposed method is potentially low cost and compatible with a wide range of PV module types.

2 MEASUREMENT METHOD

2.1 Humidity indicator cards

The humidity indicator cards selected (Fig.1) include dots approximately 11 mm in diameter constructed from blotting paper impregnated with cobaltous chloride, which is sensitive to contact with moisture. When cobaltous chloride becomes hydrated, it transforms from a blue colour to pink. Each dot contains a different concentration of cobaltous chloride, allowing them to respond to different levels of humidity [11]. It was found that by choosing the appropriate dot, measurement of more moisture levels could be achieved, as the colour of the dots changed gradually over a range of humidity levels. For this work, the dots designed to indicate levels of 40, 50 and 60% humidity were used to examine the range of relative humidity values that could be recorded.

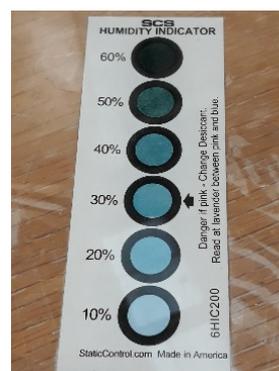


Figure 1: Humidity indicator card

2.2 Calibration procedure

Calibration of the measurement method was required, for the investigation of the representation of the different humidity levels by the different colour shades of the dots. For the calibration, three samples were measured, and the procedure below was followed:

- Encapsulation of humidity indicator cards in a laminate structure of EVA-humidity indicator card-EVA-glass (Fig. 2). This structure (with no moisture barrier on one side) was chosen to allow the fast saturation of the inner layer for a rapid calibration. Furthermore, with the EVA and the glass placed on the top of the humidity indicator card, the calibration method should be representative of the humidity measurements in a PV module, as the optical properties of the glass and the EVA layer, through which the observations are made, are exactly the same as in a module.
- Storing the laminates in an environmental chamber at 85°C and at increasing levels of relative humidity from 40% to 85%. A 48-hour dwell time was used at each humidity level (Fig. 3) to ensure that the sample was saturated.
- Measurements of the RGB colour coordinates of the three dots to be monitored are acquired by processing images of the samples taken with a camera, as detailed below. The images are acquired for each humidity level at the end of the 48-hour dwell times, and the RGB coordinates are plotted on a colour space (after transformation from the three dimensions R, G, and B to the two dimensional xy colour space), to obtain the calibration curve [12].

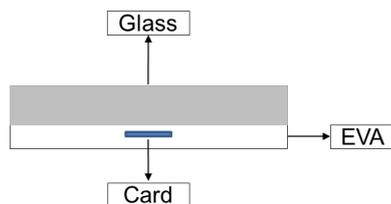


Figure 2: EVA-humidity indicator card-EVA-glass structure.

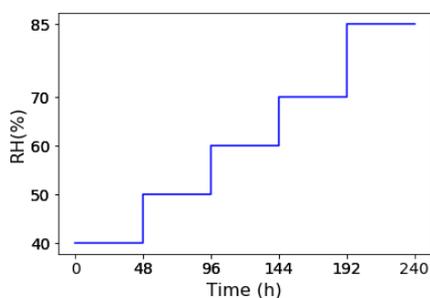


Figure 3: RH conditions for calibration of the measurement method (all at 85°C).

2.3 Camera settings

The camera used for imaging the calibration samples and the PV devices was a Canon EOS 450D. The lens aperture was set at f/8, for more repeatable colour

measurement, as less light enters the lens. In addition, the ISO of the camera was set at 100, to further reduce the sensitivity to light. The reduction of the sensitivity of the lens to light is important, so the measurements will not be affected by any slight lighting variation of the artificial light source. For these reasons, the shutter speed was very low (set at 0.8 seconds). The white balance was set to 4000-5000K, as the photos were shot under artificial light. Figure 4 shows the measurement set up.

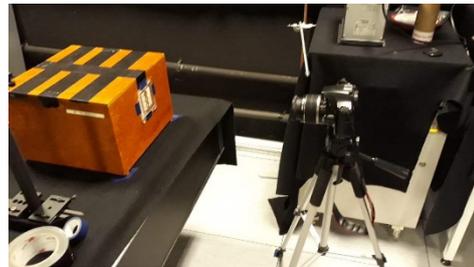


Figure 4 Measurement set up

For the verification of the repeatability of the measurements due to the stability of the room artificial lighting, before every set of sample measurements, images of blue, red and green reference cards were taken. These cards represent the red (R), green (G) and blue (B) of the RGB coordinates. Figure 5 shows the measurements of these cards before every set of sample measurements. The colour measurements of the reference cards are the same for all the sets of sample measurements.

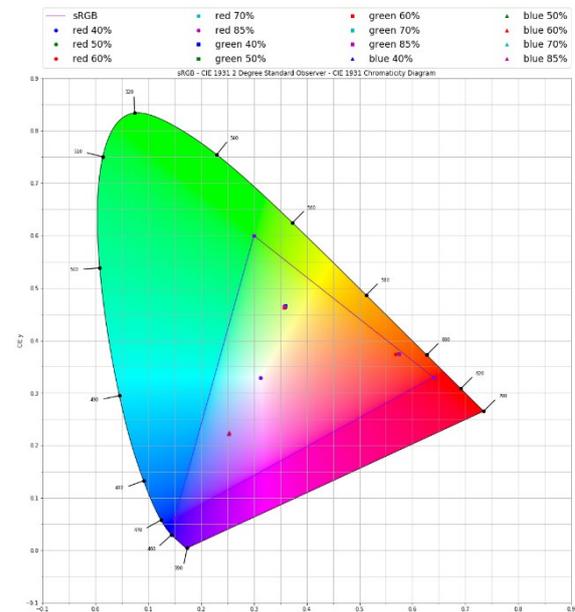


Figure 5: Repeatability of colour measurements

3 CALIBRATION – RESULTS

3.1 Calibration of measurement method

Images of the encapsulated humidity indicator cards (viewed through the EVA and glass layers) for each relative humidity level of the calibration (40%, 50%, 60%, 70% and 85%) are presented in Figure 6. The colour changes are obvious for all the dots. It is observed, that the dot that is designed to indicate a humidity of 40% changes colour earlier than the others, followed by the dot that can

indicate 50% humidity. This is because the lower the humidity that a dot can measure, the smaller is the concentration of cobaltous chloride. The surprising observation is that the dots continue to change colour even if they have exceeded the upper concentration that they should, theoretically, measure.

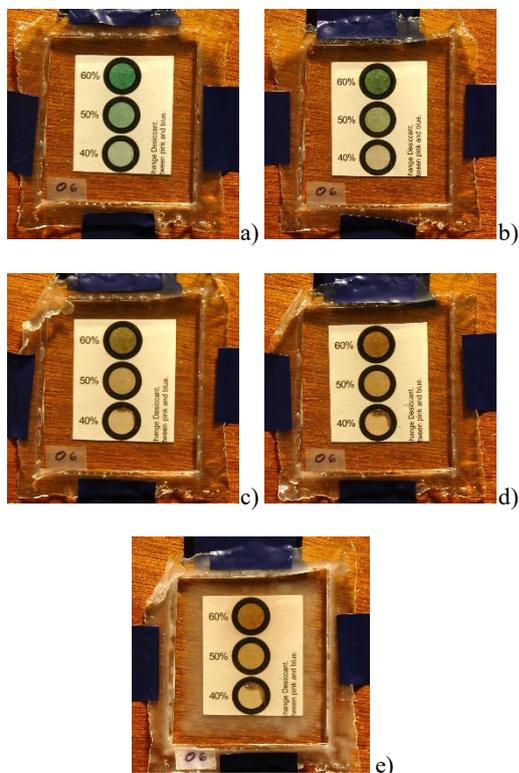
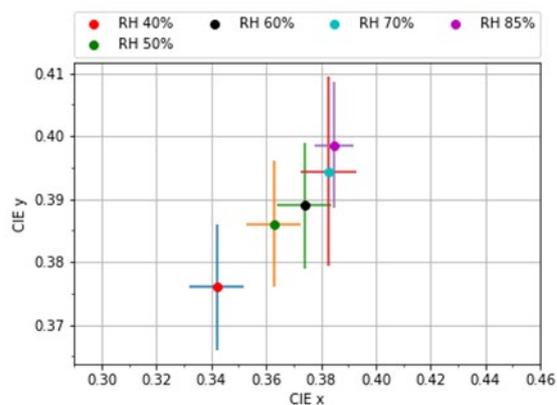


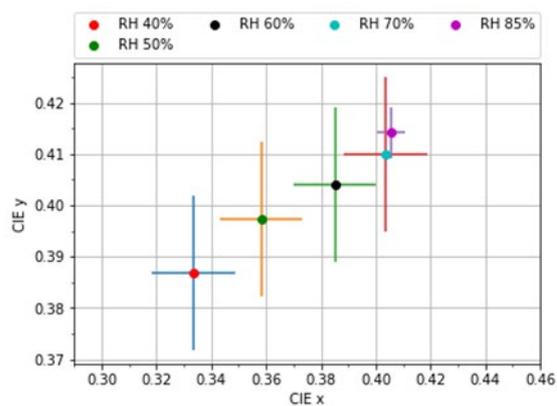
Figure 6 Appearance of the humidity indicator cards after storage at a) 40%, b) 50%, c) 60%, d) 70% and e) 85%RH.

Figure 7 shows the calibration curves for each dot. Each point is the average x and y colour co-ordinate, after transformation of the average RGB 3D coordinates to a 2D axis. The error bars indicate the standard deviation in the measurements. The error of the colour measurement is in the range $\pm 3\%$ for the dot that is designed to indicate 40% humidity, $\pm 5\%$ for the 50% dot and $\pm 6\%$ for the 60% dot. A bigger error is observed at 70% relative humidity exposure for the dot that indicates 40%, as some bubbles of different colour appeared on the sample. Furthermore, smaller errors are observed for the level of 85% relative humidity for all the dots, which is to be expected, as the remaining concentration of cobaltous chloride available to react with the moisture is much smaller. This is also the reason why the RGB coordinates for all the dots at 85% RH have similar values to those observed for 70% RH. According to the calibration curves, the smallest errors are observed for the dot that can indicate 40% humidity, but also the smallest range of measurements (x axis between 0.342 and 0.384). This is reasonable, as the concentration of cobaltous chloride is smaller. To the contrary, for the opposite reasons, the dot that can indicate 60% humidity shows the biggest errors and the largest range (x axis between 0.319 and 0.444). A larger range of values is preferred for more detailed measurements, when the calibration curves are used to estimate the moisture in a PV laminate measured by the humidity indicator cards. Therefore, the preferred dot to be used for moisture

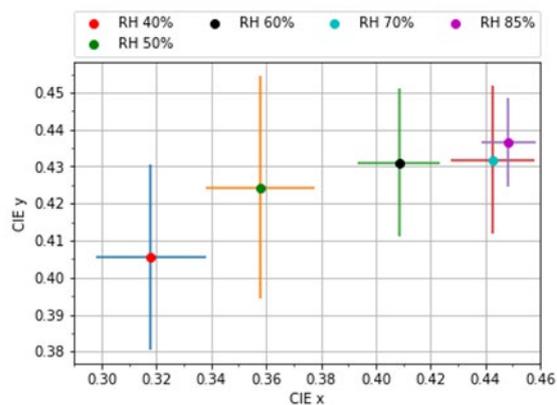
measurements is the one that can indicate 50% humidity, as it combines smaller errors and sufficient range. The evolution of the colour in correlation with the relative humidity exposure seems to be logarithmic, but further research needs to be carried out (e.g., measurement of more moisture points and curve fitting) to confirm the relationship.



(a)



(b)



(c)

Figure 7: Calibration curves for the dots designed to indicate humidity of (a) 40%, (b) 50% and (c) 60%.

3.2. Application to single cell PV modules

For a first observation of the actual behaviour of the humidity indicator cards within a PV module, dots designed to indicate 50% and 60% humidity were embedded at the front side of a PV cell, encapsulated into a PV module. The sample was then aged under 85% RH /

85 °C conditions for a total of 1763 hrs. In figure 8, the variance of the colour of the dots due to moisture accumulated at the front side of the solar cell is visible. Colour analysis was carried out for the dots indicated, which is presented in figure 9. It is observed that, after 503 hrs of exposure, the moisture level at the corner of the PV cell is around 70%, while the inner dot indicates 60% and the central dot has reached 40%. After 974 hrs, both the dot at the corner and the inner dot are saturated, and the central dot shows humidity at the level of 70%. Finally, after 1763 hrs, the whole front side of the cell is saturated. The colour of the dots seems to further change after saturation. The reason responsible for this could be the long term DH exposure that could cause further interaction of the cards with the EVA, but further research is needed for the investigation of this suggestion.

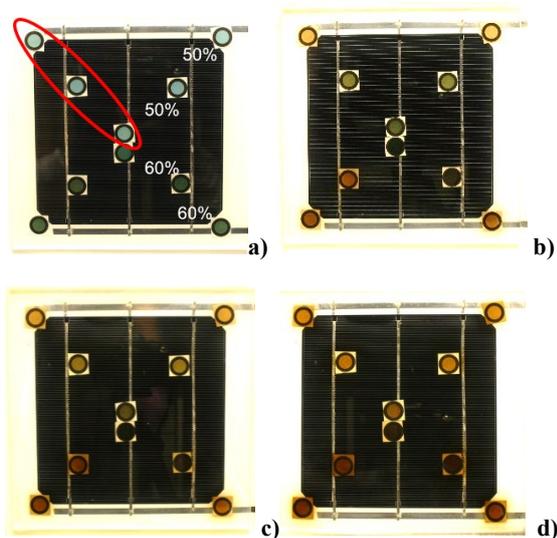


Figure 8 Single cell PV module with embedded humidity indicator cards, aged at 85% RH / 85 °C for a) 0, b) 503, c) 974 and d) 1763 hrs

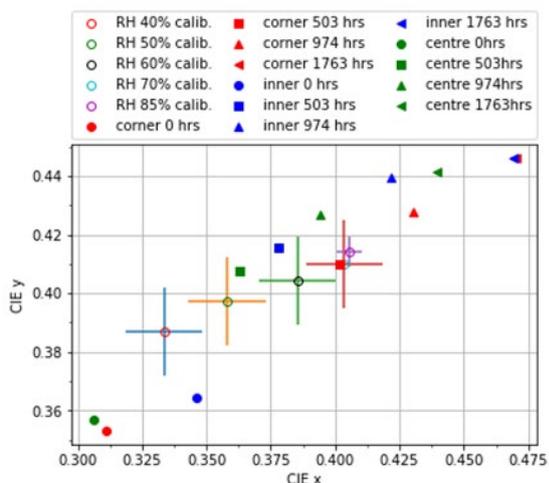


Figure 9 Colour measurements of the dots embedded at the front side of a PV cell within a PV module, compared to the calibration curve.

4 CONCLUSIONS

The purpose of this ongoing study is the development of a novel measurement method to determine the moisture that accumulates at the front side of the PV cells within a laminate structure. This measurement method involves embedding humidity indicator cards into PV laminates. To be able to use a single dot, calibration of the method needs to be completed first, for the matching of the variance of the colours to the actual relative humidity exposure levels. The optical properties of the glass and the EVA need to be included in the calibration.

From the calibration curves of the 40%, 50% and 60% dots on the humidity indicator card, it is concluded that the most appropriate one for moisture measurements is the 50% dot, as it combines small errors ($\pm 5\%$) and is sensitive over a large range (x axis between 0.333 and 0.406) of values. The errors are small enough for sufficient measurement of the moisture content, compared with the error of a measurement by a digital humidity sensor, which is equal to $\pm 3.5\%$. The variance of the colour in relation to the relative humidity exposure shows a logarithmic behaviour, but further research needs to be carried out such as measurement of more moisture points and fitting. The final curve will represent the gradual change of colours of the dots according to the respective relative humidity exposure. The colour of dots encapsulated in PV modules will be compared to the calibration curve for the estimation of the moisture level. A first attempt presented in this work shows that the measurement method developed can quantify the level of the humidity accumulated at the front side of a PV cell, within a PV module. Further research is required for the study of the interaction of the humidity indicator cards with the EVA, under long term DH exposure.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

- [1] C. Ferrara and D. Philipp, "Why do PV modules fail?," *Energy Procedia*, vol. 15, pp. 379–387, 2012.
- [2] Report Iea-pvps, *Assessment of PV Module Failures in the Field Assessment of PV Module Failures in the Field*. 2017.
- [3] A. Masuda, N. Uchiyama, and Y. Hara, "Degradation by acetic acid for crystalline Si photovoltaic modules," *Jpn. J. Appl. Phys.*, vol. 54, no. 4, 2015.
- [4] M. D. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules," *Sol. Energy Mater. Sol. Cells*, vol. 90, no. 16, pp. 2720–2738, 2006.
- [5] P. Hülsmann and K. A. Weiss, "Simulation of water ingress into PV-modules: IEC-testing versus outdoor exposure," *Sol. Energy*, vol. 115, pp. 347–353, 2015.
- [6] M. Jankovec et al., "In-Situ Monitoring of Moisture Ingress in PV Modules with Different Encapsulants," *IEEE J. Photovoltaics*, vol. 6, no. 5, pp. 2260–2264, 2016.
- [7] J. Slapsak, S. Mitterhofer, M. Topic, and M. Jankovec, "Wireless System for In Situ Monitoring of Moisture Ingress in PV Modules," *IEEE J. Photovoltaics*, vol.

- 9, no. 5, pp. 1316–1323, 2019.
- [8] T. Carlsson, J. Halme, P. Lund, and P. Konttinen, “Moisture sensor at glass/polymer interface for monitoring of photovoltaic module encapsulants,” *Sensors Actuators, A Phys.*, vol. 125, no. 2, pp. 281–287, 2006.
- [9] M. D. Kempe and J. H. Wohlgemuth, “Evaluation of temperature and humidity on PV module component degradation,” *Conf. Rec. IEEE Photovolt. Spec. Conf.*, vol. 3, pp. 120–125, 2013.
- [10] J. Kapur, K. Proost, and C. A. Smith, “Determination of moisture ingress through various encapsulants in glass/glass laminates,” *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 001210–001214, 2009.
- [11] 3M™ Humidity Indicator Cards (HICs) datasheet [Online], Available:
<https://docs-emea.rs-online.com/webdocs/1446/0900766b81446f54.pdf>
[Accessed: 15- Aug- 2019]
- [12] Python colour library tutorial [Online], Available:
<https://colour.readthedocs.io/en/develop/tutorial.html>
[Accessed: 04- Sep- 2019]