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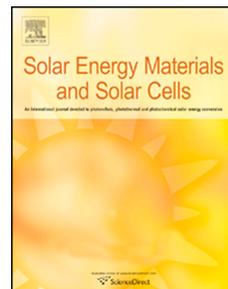
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Composite material with enhanced ultraviolet performance stability for photovoltaic modules

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Abstract

The present work aims encapsulating photovoltaic cells in glass reinforced epoxy composite by vacuum resin infusion, incorporating additives directed to enhance the performance stability of the manufactured photovoltaic modules under ultraviolet (UV) exposure.

UV absorber (UVA) and hindered amine light stabilizer (HALS) additives were incorporated in the resin system in different content. Photovoltaic performance and stability under UV radiation exposure were studied through external quantum efficiency (EQE) spectra, chromatic coordinates and short-circuit current values. Decrease in current values and increase in yellowness were observed in the presence of UVA and HALS. However, an enhanced performance stability was observed when additives are incorporated, improving the stability when increasing the additive amount. The most stable module, with cells embedded in 2% additive containing composite, showed a 2.7% short-circuit current loss after UV aging exposure.

Keywords:

Composite material

Photovoltaic module

Encapsulation

Performance stability

Ultraviolet additive

1. Introduction

Composite materials are widely employed in various industrial fields owing to their high specific stiffness and strength [1-3]. For some applications demanding multifunctional performance regarding structural and optical properties, transparent composites are of interest. Research has been carried out to obtain glass fiber reinforced composites with enhanced transparency. Iba et al. reported that the light transmittance of an epoxy matrix composite reinforced with unidirectional fibers decreases when the fiber volume fraction and fiber diameter are increased [4]. Krug et al. modified the epoxy resin with silsesquioxane compounds to match its refractive index with the one of the 0/90 cross-woven glass fiber fabric. Additionally, they worked with optically finished moulds, low seed fabric to minimize light scattering and cycloaliphatic amine curing system to avoid commonly observed yellowing [5].

One of the potential applications for glass fiber reinforced composite materials with acceptable transparency degree is solar photovoltaic modules [6,7]. Photovoltaic modules are formed by interconnected photovoltaic cells arranged in a structural and protective support. Conventional solutions are based on laminates consisting of a back sheet, front sheet and encapsulant material embedding the cells. The back sheet may be glass, polymer, metal, or combined laminates. The front sheet is usually glass or may be a transparent polymeric sheet. The encapsulant material generally consists of a polymer that flows in the lamination process embedding the cells and is adhered to the back sheet and front sheet [8,9,10]. Glass fiber reinforced composites offer an alternative encapsulant protective support, and at a first sight they could replace either the back sheet or

the front sheet. A further approach is to use the composite as the only structural and protective material replacing the whole above described module system [6].

For its use in photovoltaic modules, the composite material should have suitable durability and protect the cells and connections during the operational lifetime in varying environmental conditions including e.g. humidity, temperature, ultraviolet (UV) radiation, particle abrasion or others [10,11]. The long-term performance of the composite depends mainly on the fiber-matrix interface and properties of the polymeric matrix [12]. Degradation of epoxy-glass composite materials under natural weathering has been reported by de Souza Rios et al. [13]. The authors exposed composite laminates to a cycle of UV radiation, condensing water vapor and humidity. They observed a decrease in thermal stability and mechanical properties of elastic modulus, tensile strength and impact resistance. Additionally, degradation of the fiber-matrix interface was detected in the cross-section of the exposed surface of the composite. Similarly, other authors [14] reported mass loss, fiber exposure, increased crack density and chemical alterations of the matrix after exposure of a carbon-epoxy composite to a combined cycle of UV exposure and water condensation. Focusing on performance stability under UV radiation, photooxidation of epoxy resins has been previously studied [14-17]. The predominant sites of degradation on the epoxy polymeric backbone are the aromatic ether linkage due to its reactivity and $\text{CH}_3\text{-C}$ bond of the isopropylidene group [16]. These sites are prone to polymeric chain scission and further formation of chromophoric groups, which absorb in the visible making the composite yellowish [16, 17]. This colour change might be critical when using the composite material for photovoltaic modules. Beyond the aesthetic appearance, the yellowness of the composite in the front side of the photovoltaic

cells might decrease the amount of light that is reaching the cell, diminishing consequently the energy generation. Related to this issue, the IEC-61215:2016 standard for qualification of crystalline silicon photovoltaic modules [18] allows a maximum electric power loss of 5% after exposure to accelerated aging tests including UV radiation.

In order to enhance the environmental stability performance, composites with epoxy matrix are usually protected with a topcoat [13, 19]. In contrast, in standard photovoltaic modules with a glass front sheet, additives as UV absorbers, light stabilizers and antioxidants are usually incorporated in the polymeric encapsulant [10, 20, 21, 22] to guarantee the weathering resistance of the modules. Nowadays, there is an increasing trend to reduce the amount of UV absorbers or use low UV cut-off encapsulants in order to improve the module power output [23]. EVA (polyethylene-co-vinyl acetate) is the most widely used encapsulant polymer [9,10]. Beinert et al. [20] studied five different EVA compositions with varying presence and quantity of the mentioned UV additives, analysing the aging process with UV-Vis spectroscopy, Raman spectroscopy and Differential Scanning Calorimetry (DSC) techniques. Influence of different additives and their combination was also analyzed by Jentsch et al. [21]. The authors reported that the joint addition of UV absorber and hindered amine light stabilizer (HALS) delayed EVA degradation, whereas no effect was observed for the phosphite stabilizer or adding only the UV absorber. The HALS was identified as the key component to enhance the EVA stability. Similarly, according to the results of La Mantia et al. [22], the HALS additives can improve the photo-resistance of EVA maintaining the mechanical and transmittance properties after UV radiation exposure.

Given the potential of UV absorbers and HALS to decrease the photooxidation of polymers, their addition to an epoxy resin is considered here, which is further employed for composite manufacturing and photovoltaic cell encapsulation. The aging performance of the resulting photovoltaic modules has been examined through the evolution of colour changes and short-circuit current values obtained from external quantum efficiency (EQE) measurements.

2. Experimental

2.1. Materials and module manufacturing

Monocrystalline silicon cells (156mmx156mm) with 3 busbars were encapsulated with the composite material. The ribbons for electrical connections were welded onto the cells using a pilot-scale tabber-stringer. Afterwards, they were connected by hand welding, leading to the positive and negative connections to be used for electrical measurements. Photovoltaic modules of 250mmx250mm size and planar geometry were manufactured.

The photovoltaic cells were encapsulated by linear vacuum resin infusion process. The resin system was composed by a clear bisphenol-A based epoxy resin and an amine curing agent. The resin was selected in a trade-off between optical properties and rheological performance allowing the infusion process. A 0/90° fabric of glass fiber with a 162g/m² areal weight was used as reinforcement, placing 6 layers at the front side of cell and 14 layers at the back side. A reinforcement with an aminosilane sizing was selected in order to enhance the fiber-resin interface and minimize light dispersion.

A mould with low roughness surface finish was used consisting of a flat sheet

covered by a fluorinated polymer tape. Six fiber reinforcement layers were placed onto the mould surface, followed by the photovoltaic cells. The front side of the cells faced the mould surface. This allowed obtaining a flat composite with reduced light diffusion on the front side of the cells, not to jeopardize their photoelectrical performance. The rest of the glass fiber layers were then placed onto the back side of the cells. The described stack was covered by a peel ply. Finally, prior to the vacuum bag sealing, electrical connectors were retrieved out of the peel ply. These steps of the manufacturing setup are shown in figure 1a.

An organic UV additive from BASF was selected to be studied. This additive was supplied in liquid form and it is a blend composed of hydrophilic 2-(2-hydroxyphenyl)-benzotriazole as an organic UV absorber (UVA) and a basic hindered amine light stabilizer (HALS). The UV additive was added firstly to the curing agent and afterwards thoroughly mixed with the resin. 0.5%, 1% and 2% weight percentages of the UV additive with respect to the resin system were studied. Modules made of composite without additives were also manufactured as control samples. Some of these last modules were spray coated for UV protection using a clear varnish as topcoat.

2.2. Composite and module characterisation

The magnitude taken as a reference for the performance evaluation was the short-circuit current of the modules. The hypothesis is that when the yellowness of the resin increases, the light that reaches the cell is lowered, and consequently the current generated by the cell decreases.

External Quantum Efficiency (EQE) measurements were carried out on the modules using PVE300 equipment from Bentham. EQE values for the 300-

1300nm wavelength range were obtained every 5nm. An illuminated spot size of 3.5x1mm² was used, locating it in the area between the grid lines of the cell. Measurements were taken out at 3 points along to the central busbar of the cell, located close to it at the centre and the two edges of the cell. Short-circuit current (J_{sc}) was calculated from these data according to the following expression:

$$J_{sc} = q \int_{\lambda_1}^{\lambda_2} \phi(\lambda) EQE(\lambda) d\lambda$$

Where q is the electron charge, $\phi(\lambda)$ is the photon flux of the incident spectrum and EQE is external quantum efficiency measured on the encapsulated cell.

Colour measurements were taken out to evaluate the visual appearance and aging performance. This technique is commonly used for the assessment of outdoor organic coatings [17, 24]. CR-10 portable colour reader by Konica Minolta (d/8° sphere geometry, 10° standard observer, D65 standard illumination source) was used. A circular illuminated spot size of 8 mm diameter was used. The measurements were taken out onto the composite out of the cell location. L* lightness, and a* and b* chromatic coordinates on green-red and blue-yellow axes respectively from CIE colour space system were measured. The overall colour change (ΔE) was calculated using the following equation:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta b^*)^2 + (\Delta a^*)^2}$$

2.3. Accelerated UV exposure test

Q-UV weathering chamber (Q-Panel Company) was employed for the exposure of the modules to UV radiation. Following the IEC-61215 standard for crystalline silicon photovoltaic modules [18], the samples were exposed during 400 hours at 60°C to an overall radiation of 15.400KWh/m². The progress of the weathering was

evaluated by EQE and colour measurements carried out at the exposed modules at 50h, 200h and 400h predetermined exposure times.

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3. Results and Discussion

3.1. Module manufacturing process

The vacuum resin infusion process for module manufacturing proceeded smoothly in all cases. The front flow of the resin embedding the photovoltaic cell during infusion process can be observed in figure 1b. Complete mould filling with full coverage of the cell surfaces by the resin was achieved. No added air entrapment or bubbles were observed due to the presence of the cell and connectors. Additionally, the UVA and HALS components were homogeneously incorporated in the resin system, and no influence of their presence in the composition was detected in the infusion process.

Planar modules with a thickness of around 3mm were obtained, which were cut to 250x250mm dimensions. Front side and back side of one of the modules are presented in figure 2a and 2b respectively. Monolithic modules where the cells were completely embedded in the composite were obtained.

No major defects were observed during the qualitative assessment of the manufactured modules. No cell breakage due to vacuum forces was detected. Additionally, no delamination phenomena were observed in the cell-composite interface either in the front or the back side of the cells. Neither the ribbon-composite and connector-composite interfaces were delaminated.

3.2 EQE and short-circuit current results

Figure 3 plots the typical EQE spectra of the modules. The presence of UV absorbers is clearly evidenced in the UV cut-off wavelength of UVA+HALS compositions comparing with bare composite. Moreover, the coating used as reference initially performs similarly to the modified resin compositions, indicating

that it also probably contains UV absorbers for environmental protection. No significant influence of the additives is observed in higher wavelength values of the EQE spectra.

Detailed analysis of the UV region (figure 3b) shows that increasing the content of UVA+HALS, the UV cut-off wavelength is shifted to higher values. On the other hand, it can be observed in the graph that the resin system containing 0.5% UVA+HALS blend has the closest performance to the modules with the reference coating.

The higher absorption by the additives is directly observed in the short-circuit current values, as the light absorbed by them is not reaching the photovoltaic cell surface. The short-circuit values of the modules after manufacturing are depicted in figure 4. A sharp decrease is observed when adding 0.5% blend to the resin system, and the loss is considerably higher for 1%. The short circuit current reduction with respect to bare composite is of 0.96% and 1.96% respectively for 0.5% and 1% additive amount. The current decrease for the modules with 2% blend containing composite reaches up to 2.7%. It can be concluded from these data that up to 1% the current diminishes at a higher rate with the additive content, and from this point up to 2% the reduction slope becomes smoother. It is also observed that the performance of the reference coating, even lower than the one of the bare composite, is slightly better than the one of the resin composition containing 0.5% UVA+HALS. This is in accordance with the trend observed in b^* colour coordinate (figure 5), which indicates an increase in yellowness, being sharper up to 1% additive quantity. The UVA selected for the present work had two absorbance peaks, the first one at about 300nm and the second one at 350nm. The observed yellowing phenomenon has been previously reported [25]

for UVA having maximum absorbing wavelength over 350nm, which would be the reason of the observed increase in b^* and decrease in short-circuit current values. This in accordance with previous work [20] that found a solar transmittance loss of 1-3% when stabilizers are used.

A significant drop in photovoltaic performance of the modules is observed when incorporating UVA and HALS in the encapsulating composite. According to these results, and with expected electrical performance and cost-effectiveness in mind, it turns critical tuning their content to the minimum amount required to achieve an acceptable performance stability.

3.3 UV accelerated aging test results

The evolution of the short circuit current of the modules during accelerated UV radiation exposure is depicted in figure 6. The bare composite and compositions containing UVA and HALS present similar trend. A more pronounced decrease in the first 48 exposure hours was observed, followed by a certain stabilization up to 200h, to finalise with a less marked reduction. Conversely, the modules with the reference coating showed only a slight decrease. Increasing the UVA and HALS amount clearly contributes to the composite stability. The most stable composite, without considering the reference coating, is the one containing 2% UVA and HALS, with a 2.7% current loss at the end of the exposure. The final loss experienced by 1% and 0.5% was of 3.1% and 3.6% respectively. If it is supposed that the open-circuit voltage of the modules is constant during the weathering test, the power reduction of the modules could be estimated based on short-circuit current decrease. Here, it should be highlighted that the power loss would be below 5% in all the tested compositions, including the bare composite,

complying with the requirements of the IEC-61215:2016 standard [18]. On the other hand, comparing with glass and EVA based modules, these last ones showed a power loss up to 1.5% when exposed to 15kWh/m² under the irradiation conditions indicated by the mentioned standard [6].

The values of the chromatic coordinate b^* recorded along the exposure are compiled in figure 7. Firstly, the low change in this coordinate for the modules with the reference coating is highlighted. For the other compositions, a more pronounced increase is observed in the first 48 hours, followed by a slower yellowing rate. It has to be outlined the higher values of the 0.5% UVA and HALS containing module with respect to the bare composite along the whole exposure. Additionally, even its initial value is lower than the one of the modules containing 1% and 2% blend additive, after the weathering it turns higher. This could be attributed to the yellowing due to the UVA presence [20,21,25] combined with a lower content of HALS in 0.5% composition stabilizing the activated UVA. Other authors [21] found the importance of the HALS to stabilize the EVA encapsulant when exposed to UV radiation. On the other hand, the 1% and 2% compositions start with higher values than the bare composite, to finalize in similar values, meaning that stabilization through additives was reached. When comparing with the performance observed in short-circuit current values, it is observed that with similar yellowness, as indicated by b^* , the short-circuit current values in 1% and 2% are lower than the one in bare composite. Additionally, in the 0.5% composition, with higher b^* values than the other two UVA+HALS containing compositions after exposure, higher short-circuit currents were measured. This indicates that when forecasting the short-circuit current of a module, together with the b^* parameter, the UV cut-off shift (figure 3b) must be considered.

As closer parameters to study the performance stability, Δb^* (figure 8) and overall colour change ΔE (figure 9) were studied. Similar to the short-circuit current values, it was observed that the stability improves when increasing the UVA and HALS amount. Correspondingly, the modules containing 2% additive blend resulted the most stable ones, followed by 1% and 0.5% compositions. An improved performance stability comparing with bare composite was obtained in all cases.

3. Conclusions

Photovoltaic cells were encapsulated in glass reinforced epoxy composite by vacuum resin infusion to manufacture one cell photovoltaic modules. No major defects were observed in the modules, being the cells completely embedded by the composite.

The composite was modified with UVA and HALS additives, incorporating them to the resin system in different contents. EQE spectra, chromatic coordinates, and short-circuit current values were measured and analysed to study the photovoltaic performance and stability under UV radiation exposure. Decrease in current values and increase in yellowness were observed in the presence of UVA and HALS. However, from comparison of the response from the bare composite and the composite with UVA and HALS, an enhanced stability was observed, improving this stability when increasing the additive amount.

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Figure captions

Fig. 1. Cell encapsulation by vacuum infusion process: (a) reinforcement-cell stack and manufacturing setup and (b) evolution of the resin front flow during infusion process.

Fig. 2. Front (a) and back (b) side view of the composite encapsulated photovoltaic cell.

Fig. 3. External quantum efficiency spectra of the modules at (a) the whole wavelength range and (b) enlarged at the 380-450nm range.

Fig. 4. Short-circuit current values as a function of UVA and HALS content in as manufactured modules.

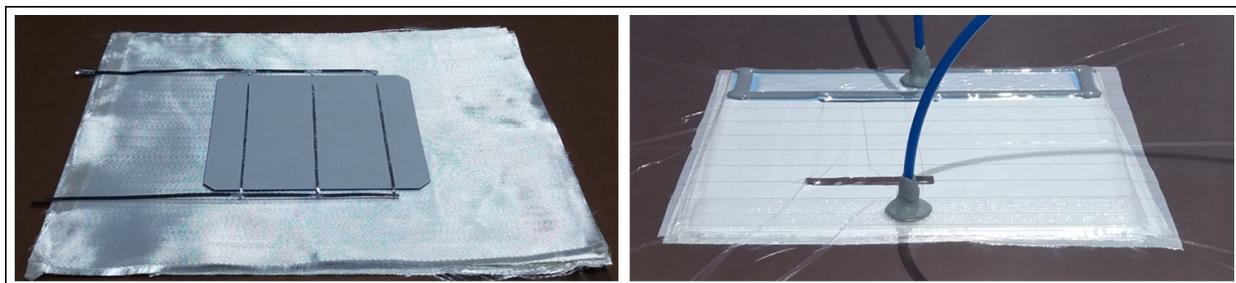
Fig. 5. Values of b^* chromatic coordinate as a function of UVA and HALS content in as manufactured modules.

Fig. 6. Short-circuit current variation as a function of UVA and HALS content and UV radiation exposure time.

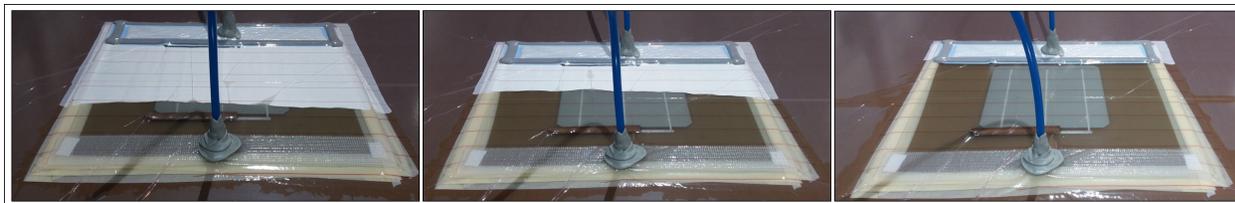
Fig. 7. Values of b^* chromatic coordinate as a function of UVA and HALS content and UV radiation exposure time.

Fig. 8. Variation of b^* chromatic coordinate as a function of UVA and HALS content and UV radiation exposure time.

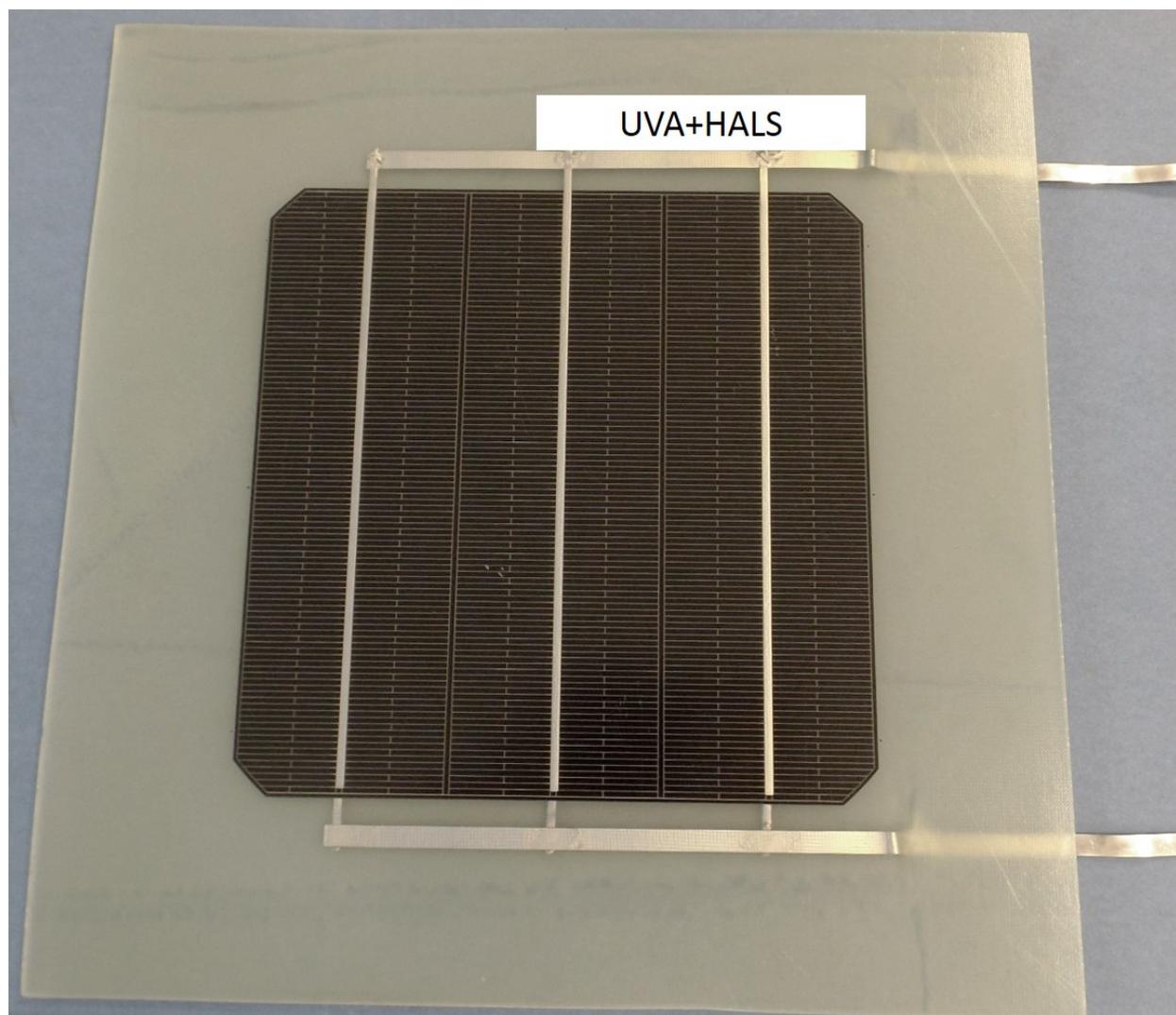
Fig. 9. Overall colour change (ΔE) as a function of UVA and HALS content and UV radiation exposure time.



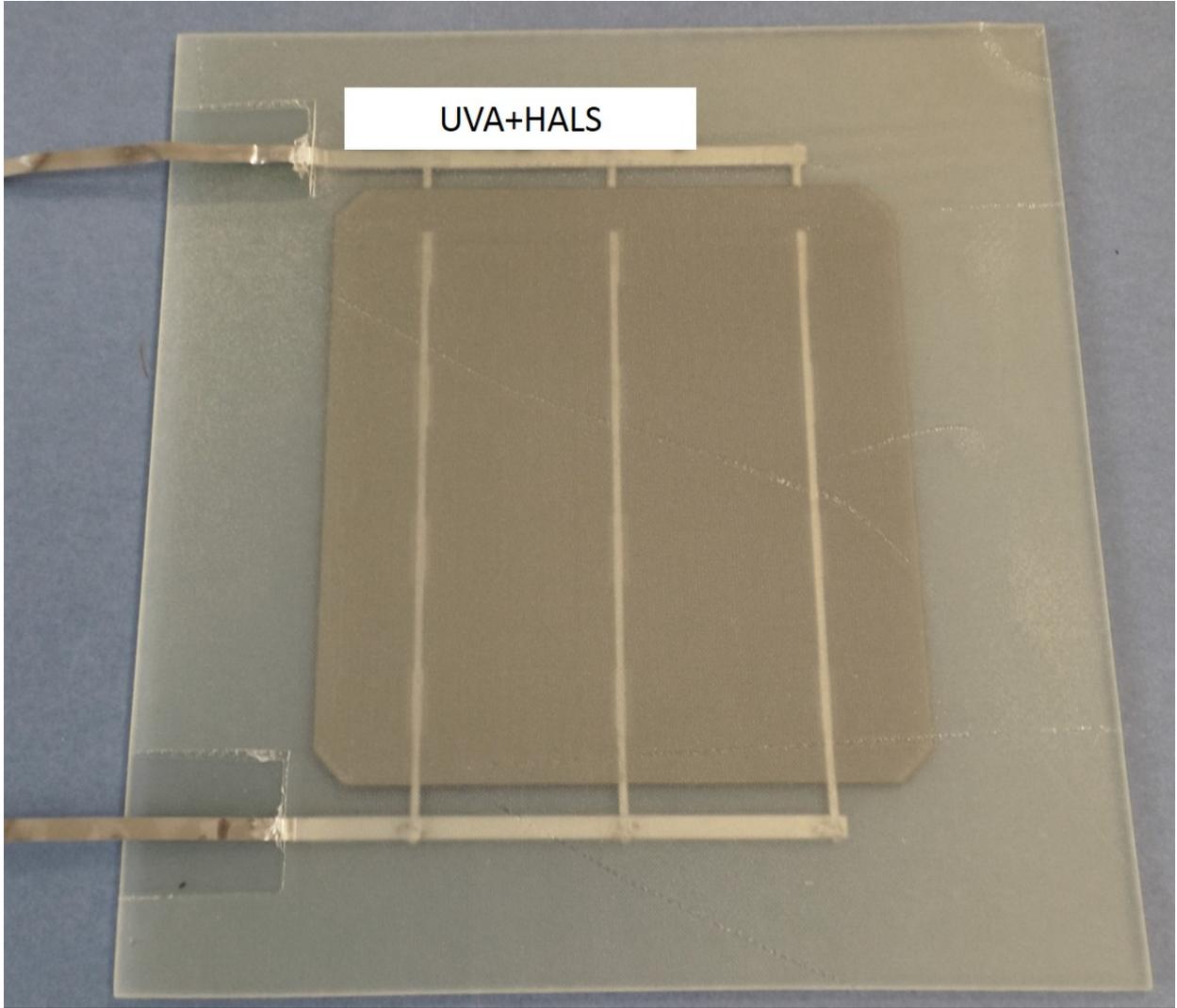
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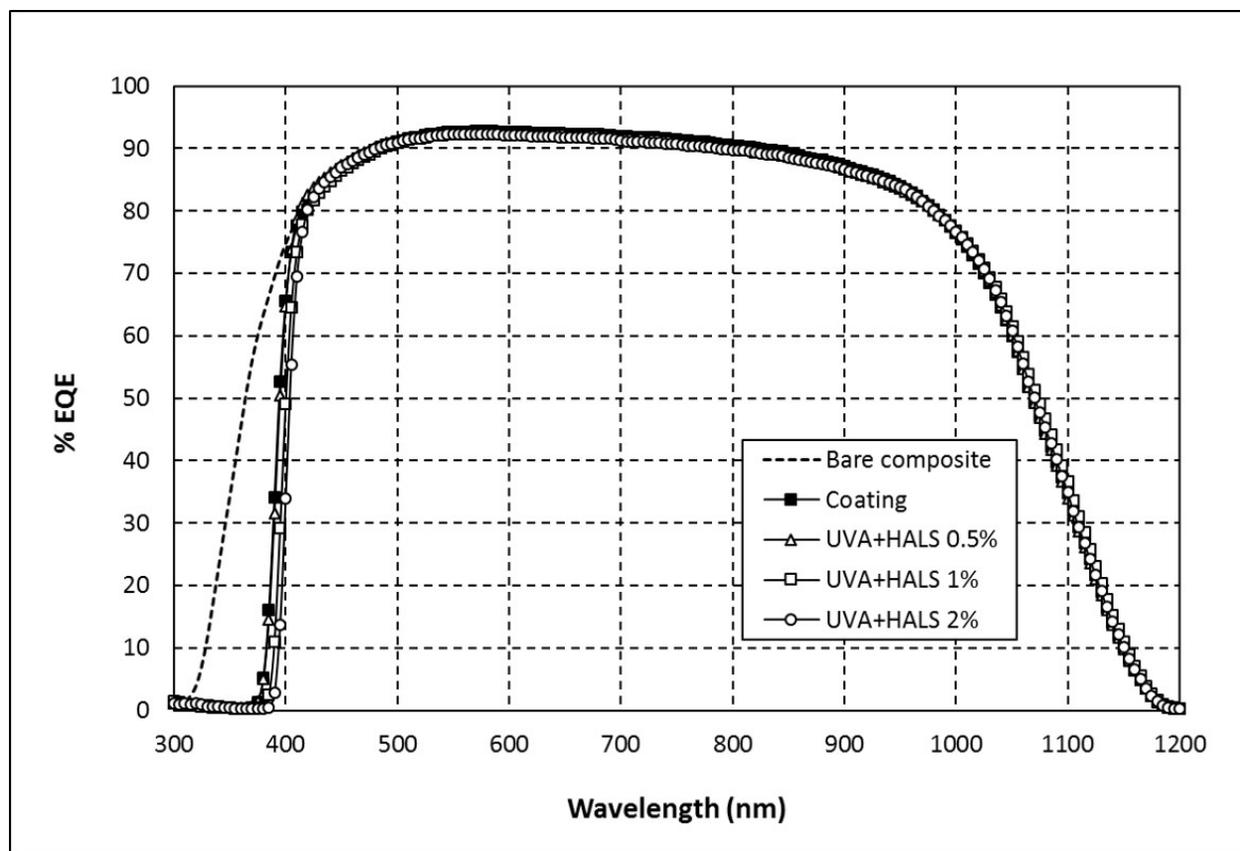
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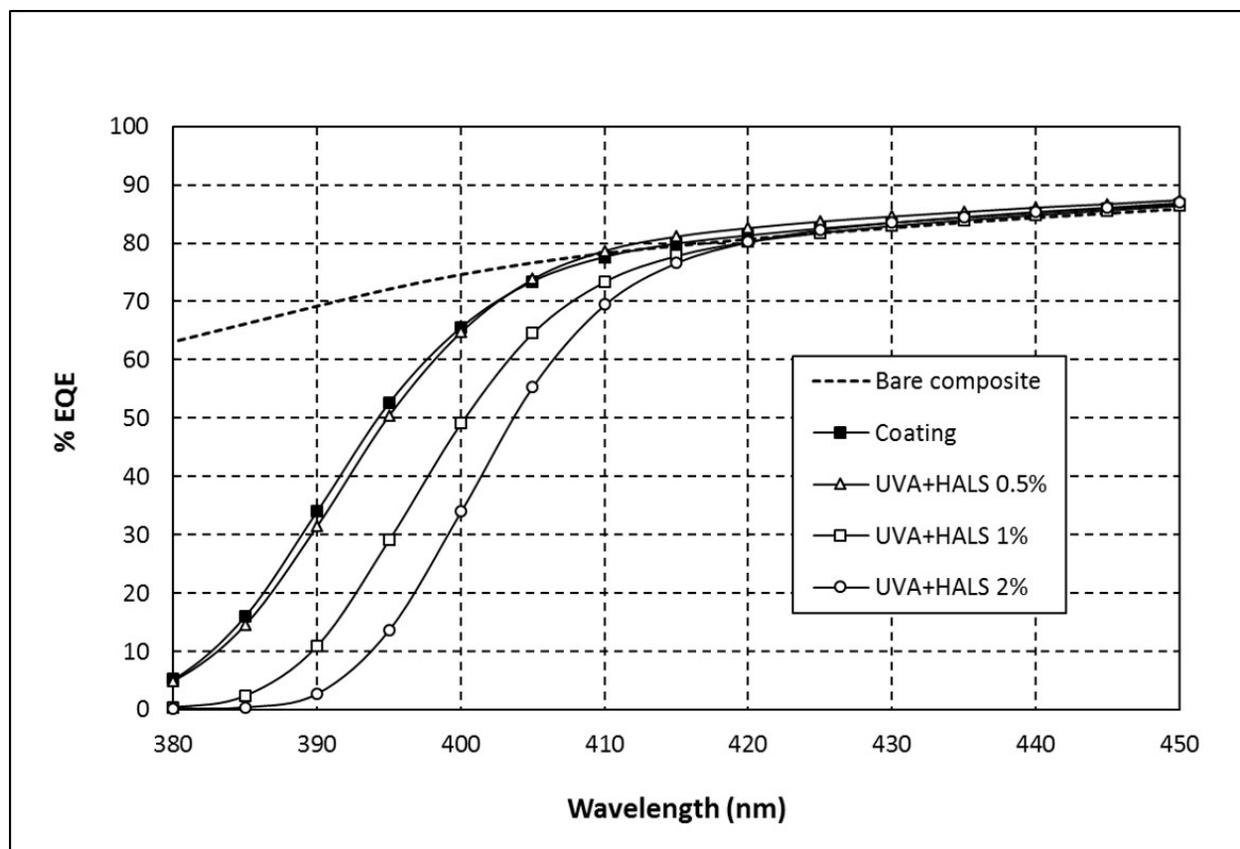


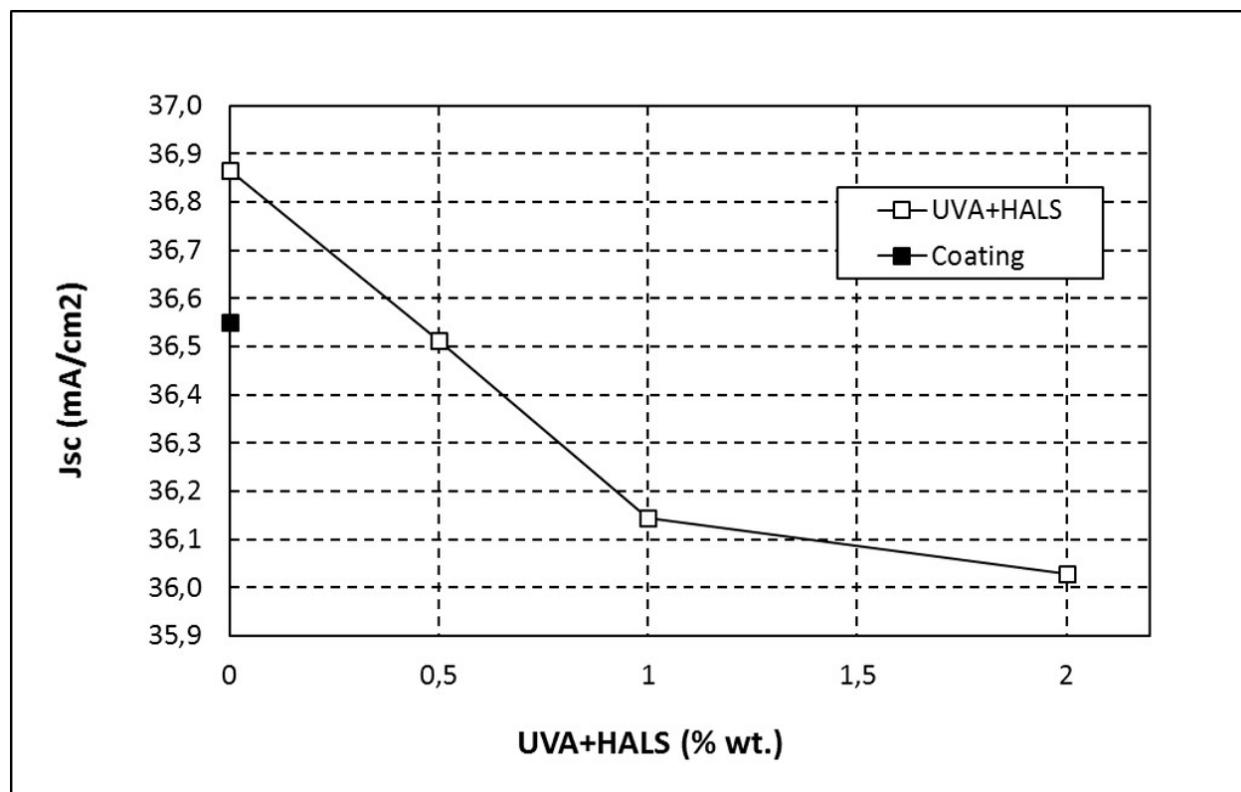
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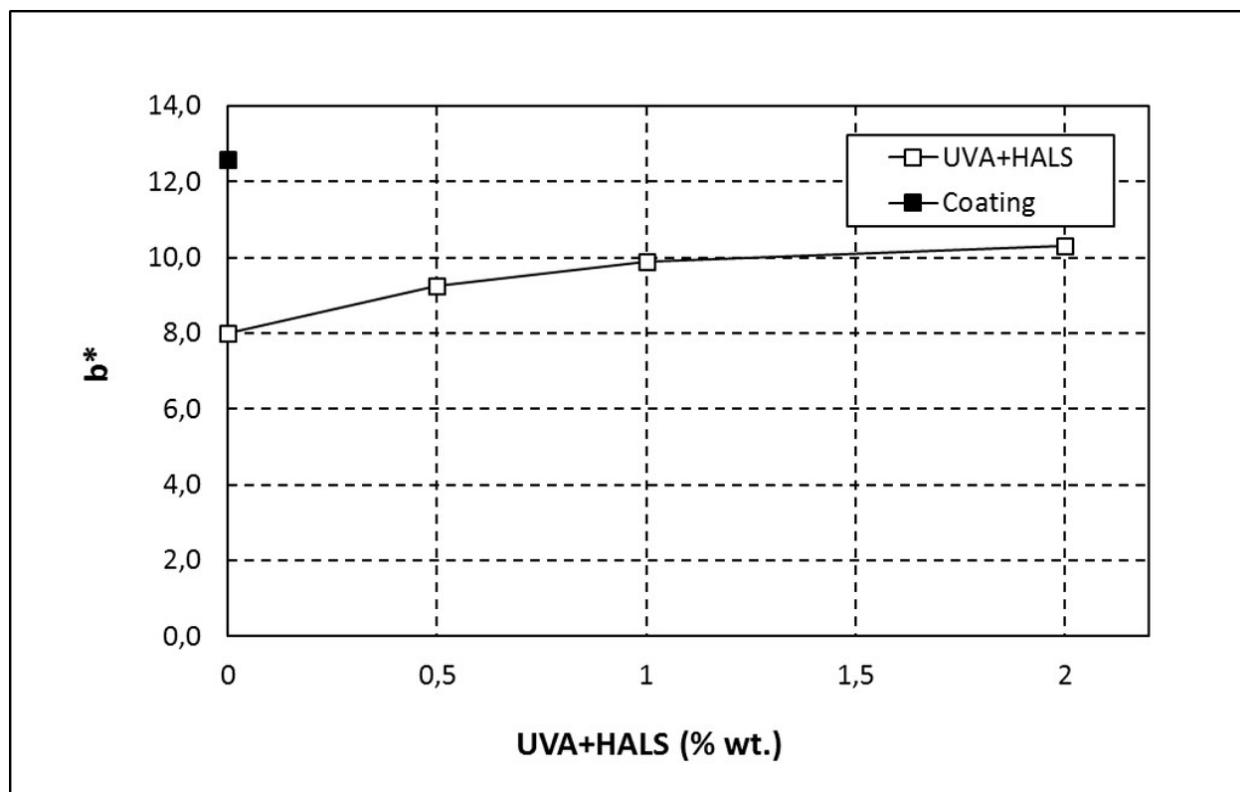
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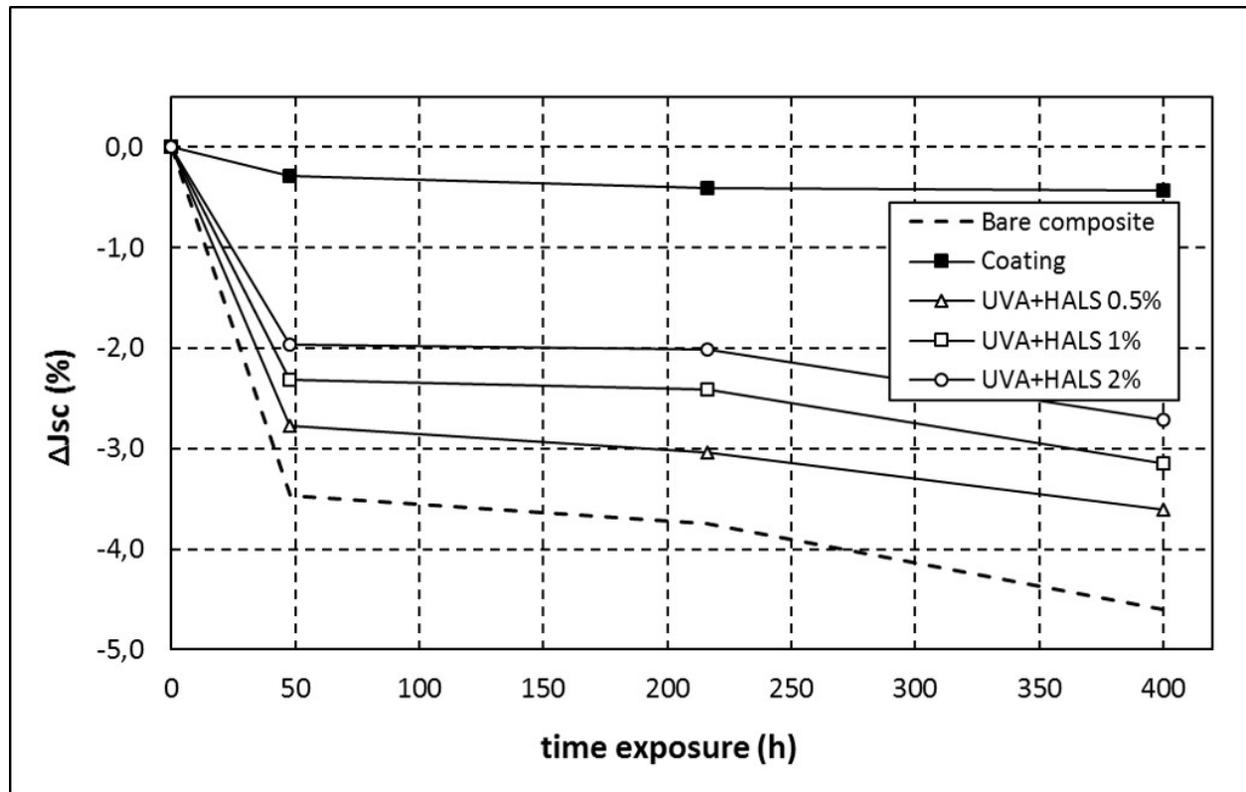


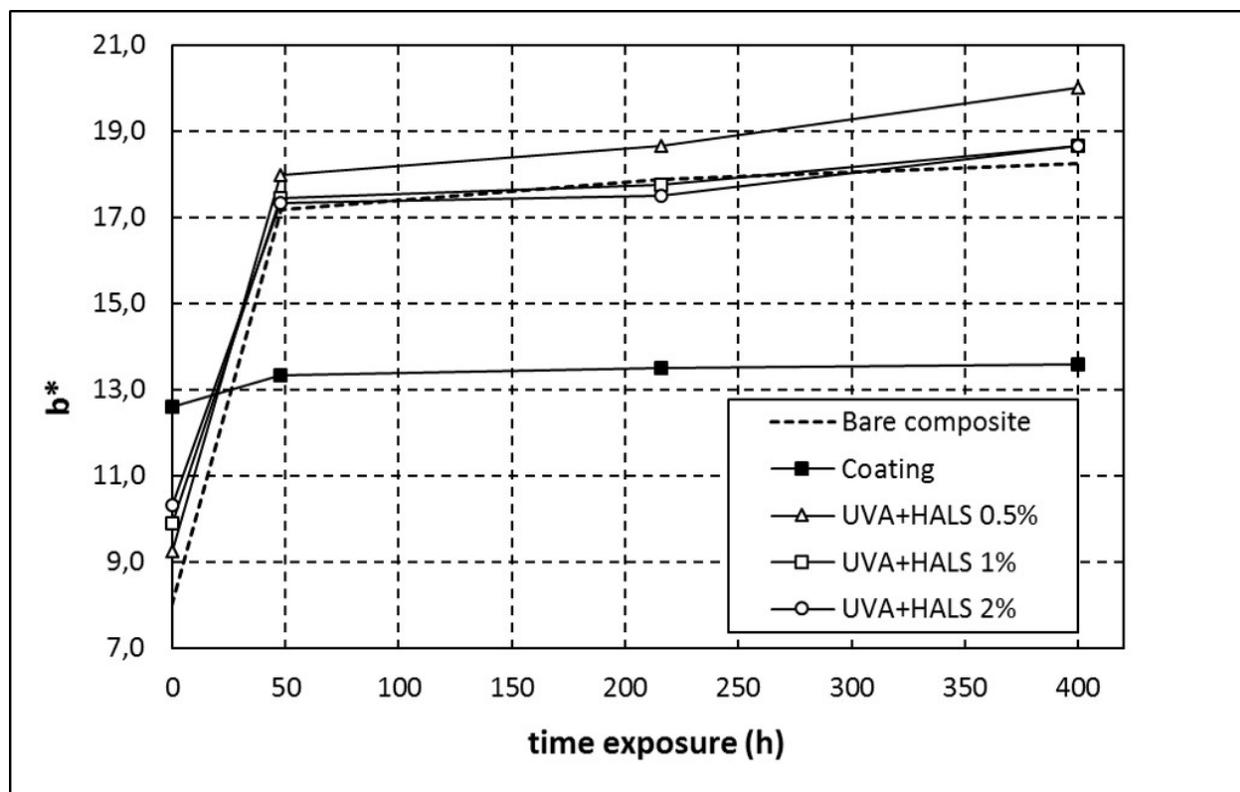


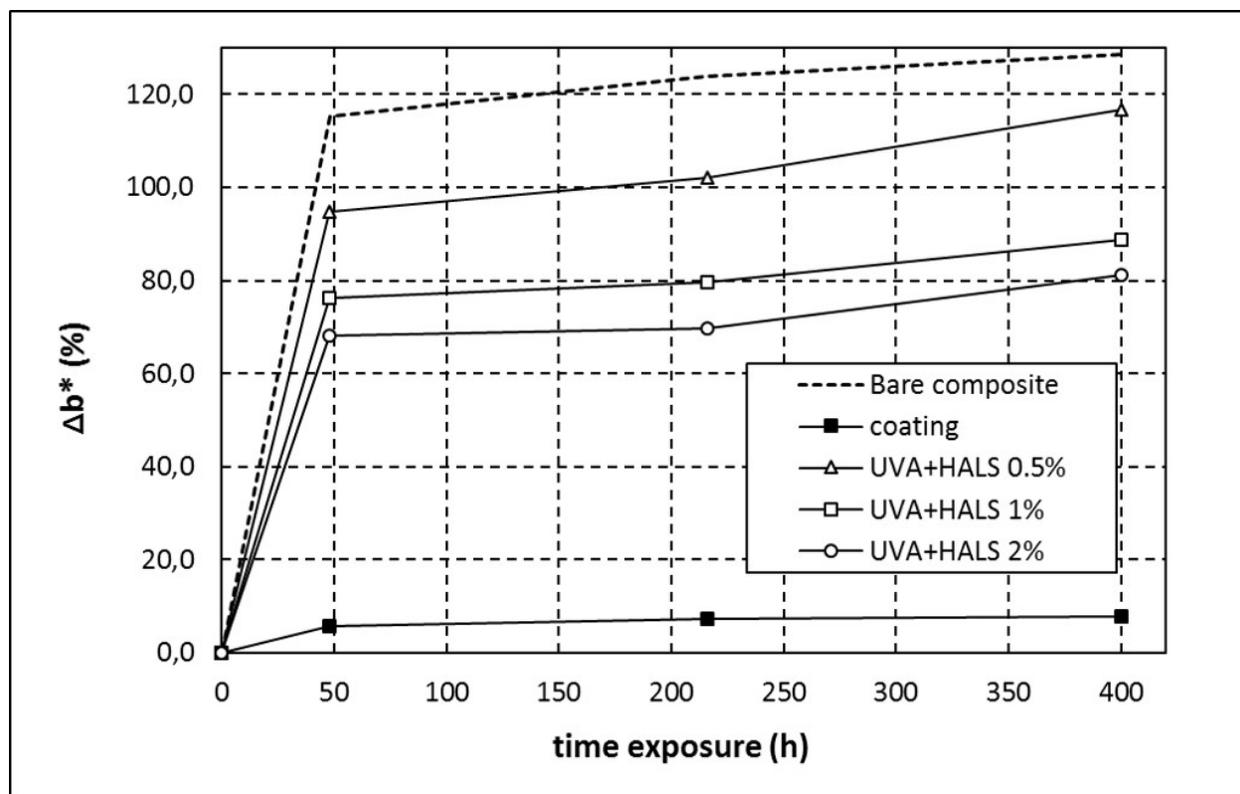
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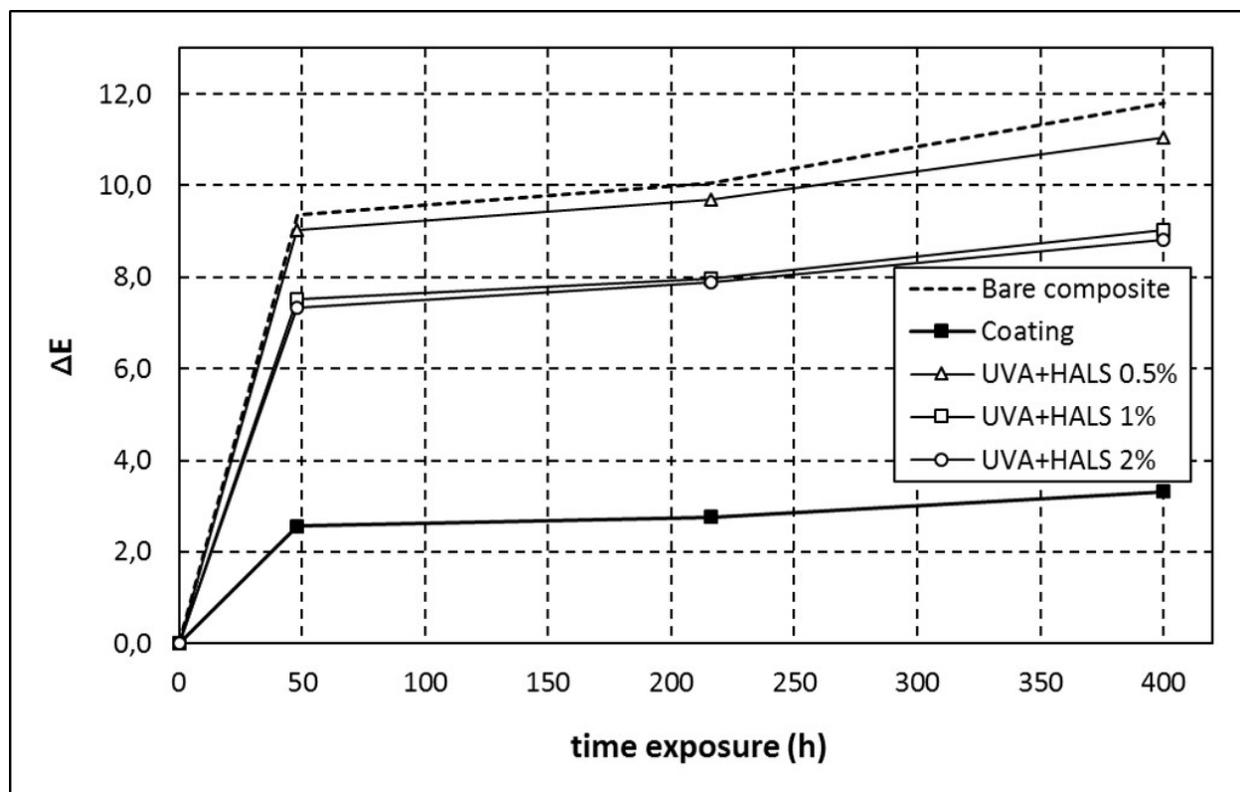


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- Photovoltaic cells were encapsulated in glass reinforced epoxy composite
- The composite was modified with different contents UVA and HALS additives
- Enhanced ultraviolet stability was observed though in a trade-off with optical performance

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