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Degradation of Bisphenol-A-polycarbonate (BPA-PC) Optical Lenses under Simulated Harsh Environment Conditions

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Abstract

This paper investigates degradation and failure mechanisms of BPA-PC lenses in simulated harsh environment conditions. Exposure of secondary optics in Light Emitting Diode LED-based systems or any other similar applications to environmental stresses can adversely effect the performance and lifetime of products. This paper simulates a harsh environment condition, using a salt bath oven. Salt spray exposure/ageing tests at 45˚C were carried out up to four months. Fourier transform infrared-attenuated total reflection FTIR-ATR spectrometer and Lambda 950 Ultraviolet-Visible (UV-VIS) spectrophotometer were used to study the optical and chemical characteristics of aged plates. Results showed that salt bath exposure test resulted in the severe deterioration of optical characteristics BPA-PC samples. Degradation of optical properties of BPA-PC plates is attributable to the oxidation of samples.

1. Introduction

Light emitting diodes (LEDs) are nowadays widely used for lighting purposes. They will soon take over the whole lighting market. LEDs are known to be economic option, with less impact on the environment, i.e. light emission in LEDs necessitates less energy consumption, compared to traditional light sources. Figure 1 shows how this will affect total energy consumption in lighting market up to 2030.

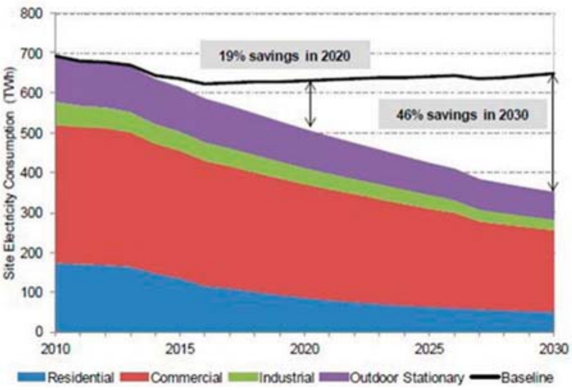

Figure 1: *Electrical energy consumption in the lighting market, in case traditional light sources are replaced with LEDs (after US DOE, August 2014).*

Failures and degradation of solid state lighting (SSL) devices can take place in different components and levels [1]. Mechanical, chemical, and thermal stresses inside the package/device are major causes of failures. Figure 2 shows examples of well-known package related failure mechanisms in SSL devices. Many of observed failures in SSL devices are related to the LED chip/package and solder interconnects [2,3]. A few examples are degradation of Ohmic contacts [2], failures in the lead frames [3–5], discoloration of encapsulant materials [6], carbonization of encapsulant materials [7,8], and thermal quenching of phosphor [9].

Package-related Failure Mechanisms in LEDs

Failure Mechanism	Failure Mode	Failure Cause	Effect on Device
Carbonization of Encapsulant	Lumen Degradation	High Current-Induced Joule heating or High Ambient Temperature	Electrical Overstress
Delamination	Lumen Degradation	Mismatch in Material Properties (CTEs and CMEs)	Thermomechanical Stress
		Interface Contamination	
		Moisture Ingress	Hygro-mechanical Stress
Encapsulant Yellowing	**Lumen Degradation, Color Change, Dislocation of the Encapsulant**	**Prolonged Exposure to UV**	**Photodegradation**
		High Current-Induced Joule Heating	**Thermal Stress**
		Presence of Phosphor	
		High Ambient Temperature	
Phosphor Thermal Quenching	**Lumen Degradation, Broadening of Spectrum (Color Change)**	**High Current-Induced Joule Heating or High Ambient Temperature**	**Thermal Stress**
Lens Cracking	Lumen Degradation	High Ambient Temperature	Thermomechanical Stress
		Poor Thermal Design	
		Moisture Ingress	Hygro-mechanical Stress
Solder Joint Fatigue	Lumen Degradation, Forward Voltage increase	Mismatch in material properties or Thermal Cycling Induced High Temperature Gradient	Mechanical Stress
			Cyclic Creep and Stress Relaxation
			Fracture of Brittle Intermetallic Compounds

Figure 2: *Identified failure modes in LEDs.*

To control the light output, emitted from a LED light source, a secondary optic is used. Glass, polymethylmethacrylate (PMMA), polycarbonate (PC), and silicone are various optically transparent materials that are often used as the secondary optics. The latter is a rather comparatively cheap option, known to have a very good structural stability during service exposures. The main drawback of PC, as secondary optics, is the discoloration under long time UV exposure [10]. Silicone is a relatively new choice, with higher discoloration resistance, higher thermal stability, easier curing process, higher flexibility, and superior mechanical properties, compared to PC and PMMA [11]. There is a rather good understanding of the correlation between mechanical/thermal/chemical stresses and failures in SSL systems. However, existing knowledge in the literature on this issue is mostly based on the laboratory experimental tests in controlled conditions. Hardly is there any information on the degradation of SSL devices under harsh environment working conditions. Types and aggressiveness of stresses in harsh environment working conditions are largely different than those in the indoor controlled conditions. Several stresses, including ionic and saline water stresses, are only effective in harsh outdoor conditions. Existing knowledge on the correlation between harsh environment stresses and degradation and reliability of LED packages is very limited. LEDs are increasingly getting more attention in industrial and outdoor applications. LEDs will soon replace

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traditional light sources in these market domains. A few examples of outdoor applications are shown in Figure 3.

Figure 3. *Outdoor applications LEDs in street lighting and industrial areas.*

The main controlling factor in the lifetime and reliability of LED lenses is the aging of optical materials during outdoor service. Ageing and degradation of optical lenses result in a color shift and lumen depreciation. Both color shift and lumen decay have negative contribution to the lifetime and performance of LED-based products such as lamps and luminaires. When it comes to harsh and aggressive outdoor environment exposure conditions, stresses, such as temperature, moisture, radiation, oxidation, and combination of these factors have major attributions to the ageing/degradation of BPA-PC lenses. Hardly is there any report in which the correlation of these stresses with the failure of BPA-PC plates is investigated. Existing literature is mainly limited to controlled thermal/ light exposure tests [13,14]. There are loads of research on the prediction of the lifetime of LED-based products and LED packages under light/thermal stresses [15–18]. In order to get the results in a reasonable time, ageing tests must be accelerated. Accelerated lifetime testing is principally based on the exposure of samples to high levels of ageing stresses, i.e., higher-than-normal light intensity, high temperature, and high humidity [19,20]. Yet, there are major concerns on the credibility and applicability of these models in real outdoor working conditions. The main objective of this study is understanding the mechanisms of degradation of optical properties of harsh-environment-exposed BPA-PC lenses, in a simulated saline environment. The data and results, obtained in this research, will be useful when it comes to the improvement of LED-based products for outdoor environment applications.

2. Materials and Methods

Commercial BPA-PC samples of 3 mm thickness were aged up to 5 months, under salt spray test at 45°C. Samples were put in the salt spray chamber at 45°C, containing water with 3 wt% salt. Fourier transform infrared (FTIR) spectroscopy was used in order to study the effects of ageing on the chemical structure of samples. Lambda transmission spectroscopy was used to study the optical properties of specimens. Application of different stresses in performing accelerated degradation tests has already been reported [17]. Amongst different stresses, temperature and humidity are more often used to accelerate ageing of optical materials [17]. To our knowledge, there is no report on the ageing and accelerated degradation tests of BPA-PC LED lenses under a salt spray test condition. Optical lenses in LED-based products in many industrial areas and sea atmospheres are exposed to saline humid atmosphere. This research is a step forward in building up and in-depth understanding of the degradation mechanisms and the reliability of BPA-PC lenses in LED-based products in outdoor environments.

3. Results and Discussion

Figure 4 illustrates the UV-Visible light transmittance spectra of BPA-PC lenses, degraded under salt spray test conditions. As on can anticipated, the light transmission is reduced by increasing exposure time in the visible light range, indicating that the quality of BPA-PC plates has depreciated with exposure time. Combining both saline and high-temperature conditions has severe adverse effects on the optical properties of the samples. Saline water spray test at 45°C resulted in a significant drop in the transmission of samples in the visible light range, reduction in the maximum radiant power at 450 nm (see Figure 5), and a change in the color chromaticity values.

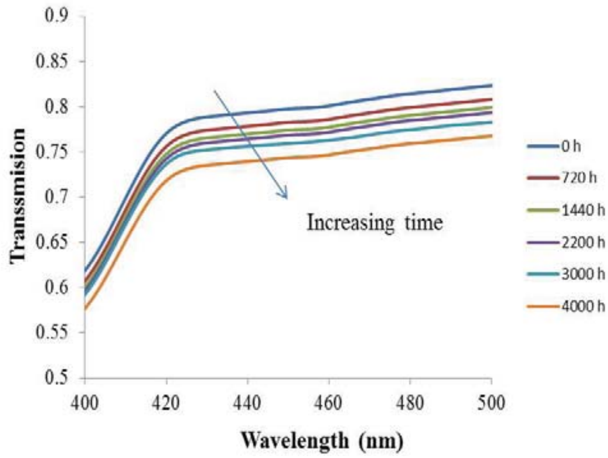

Figure 4. *Variation of maximum power intensity at 450 nm with exposure time under a salt spray environment condition at 45°C.*

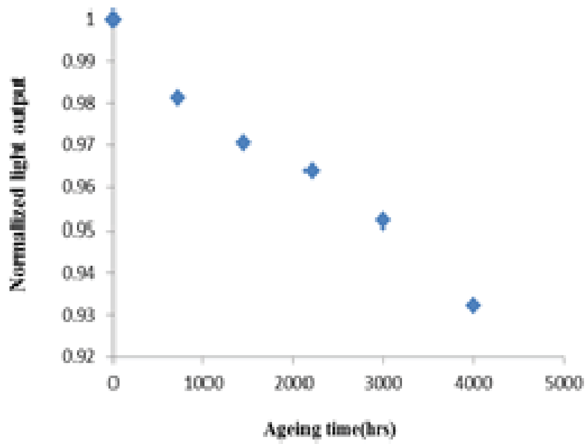

Figure 5. *Variation of maximum power intensity at 450 nm with exposure time under a salt spray environment condition at 45°C.*

Table 1 shows the chromaticity values of degraded samples. X Y Z values of degraded specimens show the shifting of the light towards yellow region.

Table 1. *Variation of chromaticity values with exposure time in saline water-exposed specimens.*

Exposure Time (h)	X	Y	Z
As-received	0.256	0.140	0.610
720 h	0.266	0.143	0.600
1440 h	0.278	0.153	0.570
2200 h	0.282	0.167	0.582
3000 h	0.285	0.165	0.575
4000 h	0.290	0.170	0.550

FTIR-ATR spectra of aged BPA-PC under salt-spray conditions is shown in Figure 6. Spectra are between 900 cm^{-1} and 1850 cm^{-1} bands (spectra are normalized using the peak located at 1014 cm^{-1}.). As it is seen the transmission at this region decreases with radiation time. Looking at the FTIR spectra, one can conclude that chemical degradation was associated with formation of acid. The decrease in the transmission of degraded samples with exposure time in this case is quite significant. Looking at the FTIR spectra, one can conclude that chemical degradation was associated with the formation of 1690 cm^{-1} (aromatic ketones) and 1840 cm^{-1} (cyclic anhydrides) bands, in the FTIR-ATR spectra of degraded specimens certainly confirms oxidation reactions respectively.

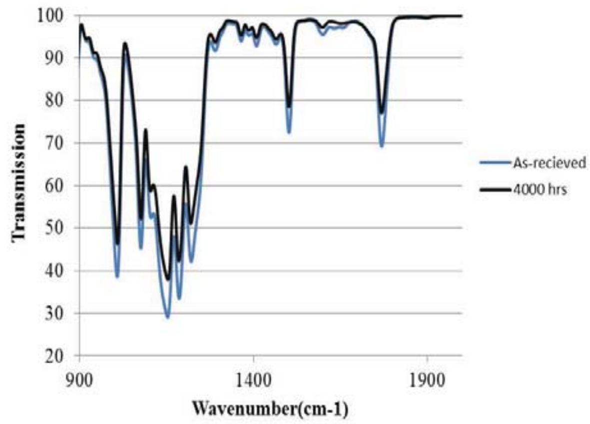

Figure 6. *FTIR-ATR spectra of samples exposed to salt-spray test at 45°C.*

4. Conclusions

The degradation of BPA-PC used as lens in LED-based products under aggressive saline environment conditions was studied. The effect of applying both temperature and moisture in the salt-spray chamber (45°C), on the depreciation of light characteristics which are color shift, transmission, and decrease in radiant power intensities of BPA-PC samples were investigated. The major conclusions of this study can be summarised as bellow:

- Exposure to moisture and high-temperature conditions has negative effects on the optical characteristics of samples.
- Saline water exposure at 45°C resulted in a significant reduction in the transmission of samples in the visible light range, reduction in the maximum radiant power at 450 nm, and a change in the color chromaticity values.
- Oxidation of the BPA-PC is the main chemical change in aged BPA-PC

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