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RESEARCH ARTICLE

An Experimental Investigation on the Role of LEDs on the Lifetime Performance of Consumer LED Luminaires

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ABSTRACT Solid-state lighting technology currently dominates illumination technologies, which have been growing throughout time. LEDs are a semiconductor-based illumination solution that is energy-efficient, long-lasting, and capable of meeting all application requirements for quantity of light, colour and spatial limitations. In all of the essential lighting applications, LED reliability and lifetime performance are critical. The LED luminaire's performance may decline over time, resulting in lower light output or different colours than the required colour characteristics. The importance of LED performances in LED luminaires as a system has only lately been realised. Different LEDs are used in two commercially available LED luminaires with exact electrical and optical specifications that are exposed to accelerated working conditions. The paper outlines a method for analysing and forecasting lifetime based on lumen maintenance for light output, Duv for colour-based quantification. The xy chromaticity, spectral power distribution, scanning electron microscopy and energy dispersion spectroscopy analysis are used to detect the characteristics indicative of variations in LED light output performance with degradation. The findings imply that LED packaging and device physics are important factors in the LED luminaire's overall lifetime performance. The work gives consumers the opportunity to see specifics about luminosity and colour-based changes as a product data-sheet, making it easier for them to choose appropriate luminaires for their needs. It also aids LED and LED luminaire makers in making appropriate design and technological adjustments, resulting in improved LED performance that is long-lasting and consistent in colour stability.

INDEX TERMS LED reliability, spectral power distribution analysis, SEM-EDS analysis, LED phosphor degradation.

I. INTRODUCTION

LED technology's versatility to suit any shape and size, energy efficiency, and a long lifetime of around 50,000 hours have helped it to surpass any other lighting technology [1]. In the last decade, the LED driver reliability has addressed LED luminaire system reliability. However, because of the developments in power electronics and components, the driver's lifetime has significantly increased. The LED performance in the LED light engine primarily influences the LED luminaire system's reliability. In addition, numerous new LED luminaire manufacturing businesses have sprouted in response to market demand for LED-based lighting solutions for general illumination applications. To save money, manufacturers may employ a lower-quality economic class of LEDs, jeopardising the LED luminaire's reliability. According to recent studies in [2] and [3], the primary cause of LED luminaire failure is the degradation of the LEDs themselves, with driver electronics failure as a secondary cause.It is vital to investigate the quality of LEDs used and their behaviour as a system in order to offer long-term life performance metrics for LED luminaires. Many studies and analyses [4], [5], [6] show that the LED package and phosphor play a significant influence on the overall LED system's degradation physics under varied ambient situations. Reference [7] suggests that the failure mechanisms associated

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with the LEDs can be accounted by analysis of the spectral power distribution of the LEDs with help of statistical curve-fitting. The work also suggests the useage of spectral power distribution curve for analysis of colour based parameters of an LED. The influence of junction temperature on Spectral power distribution fluctuations and the ratio of white to blue light power is studied in [8] and [9] for possible LED deterioration by the operating temperature. The work presented in [10] suggest an in-situ measurements and early detection of failure or possible anomalies in an LED by thermal and electrical measurements from an LED. The work presented in [11], provides a review of various prediction models and tools to determine the reliability of the LEDs and LED luminaries. A data driven approach [12] and particle filter [13] based lifetime prediction of lumen maintenance is adopted and lifetime in terms of lumen degradation is predicted. LED Lifetime prediction of LED light engine using Bayesian method is presented in [14]. The prediction is done for a high power LED with accuracy and lifetime and comparison with existing TM-21 is also presented in [15].

The thermal stress limit for noticeable physical variations and a short-term accelerated degradation test is conducted in [16]. The observation shows a considerable reduction in light output as well as darkening of the epoxy hue. Reference [17] proposes experimentation at 25°C and 85°C and determines the lumen degradation for an LED luminaire considering the effective performance of each subsystem. The results show that the LED is primary source of failure followed by the secondary optics and then the LED driver electronics. The work presented in [18] uses step based stress technique for accelerated degradation testing and the spectral characteristics is observed. The results are used to determine the lifetime for each stress condition. Reference [19] determines the time to failure by analysing the reliability of steady-state life tests, temperature humidity bias, and pulsed life tests under defined testing conditions. Reference [20] recommends a process of testing to analyse the effects of the accelerated condition on LED luminaire's performance as well as reliability prediction. The research given in this paper is primarily concerned with LED luminaire criterion for failure such as light and colour-based lifespan performances. Many more works of literature, such as [21] and [22], use simulation, analytics, and experimental study to examine the differences in SPDs during the degradation of mid-power LEDs. The findings support the hypothesis that the phosphor layer and LED packaging material qualities are the primary causes of degradation. As the LED luminaire market is vast, many manufacturers are providing LED based lighting solution for general applications. For promoting products, one strategy is to provide LED luminainres at relatively lower price by using a particular class of LEDs of same series. Thereby market available LED luminaire reliability analysis is of importance. The lifetime predictions at system level for LED luminaire can be made with IES-TM-28-14 [23] and/or IES-TM-21-11 [24]. However, these methods perform the experimentation and use the

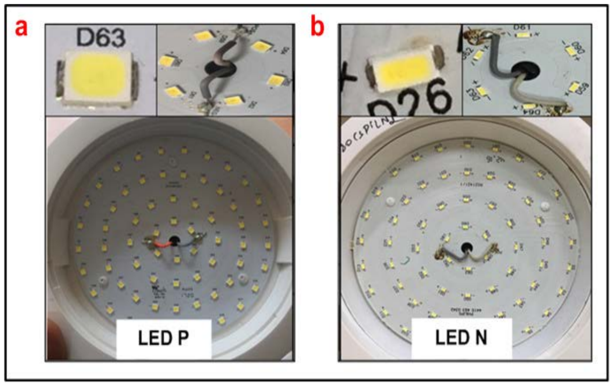

FIGURE 1. LED test samples: 1a. corresponds to luminaires referred as LED P and 1b.corresponds to luminaires referred as LED N.

Arrhenius equation to predict a single failure mechanism of light output. The testing is carried out for 3000 hours with a sample every 500 hours; thereby, the nonlinear degradation nature is not accurately considered as the experimentation duration is not till the failure of the LED luminaire. The reliability and failure mechanisms of color-based variations and the primary failure mechanisms at device level leading to light output degradation/color shift are not described. However, LM-80/TM-21 prediction is made for individual LEDs, and the lifetime prediction is based only on lumen maintenance alone. The reasons for severe lumen degradation or color degradation at the LED package level are not explored. The work presented in this manuscript addresses the research gap in identifying the reason for LED luminaire failure (be it lumen or colour based), specifically for the LEDs used in market available LED downlighters. This paper is organized as follows; Section II describes the general methodology adopted with the test device and setup description. In Sections III shows the lifetime performance, analysis, and discussions of the results. Section IV draws the conclusion.

II. METHODOLOGY

The study involves subjecting LED luminaire samples to two levels of accelerated deterioration testing (ADT), referred to as Accelerated degradation test scenario 1 (ADTS1) and Accelerated degradation test scenario 2 (ADTS2), respectively. The test condition of ADTS1 has a fixed ambient temperatures of 80°C with relative humidity of 80% RH, while test condition ADTS2 has 60°C with 80% RH as temperature and relative humidity respectively.

The LED luminaire samples included in the investigation are from a renowned LED lamp manufacturer's marketplace available luminaires. The samples of LED luminaires with equal electrical, mechanical, and optical properties were chosen at random and only the LEDs utilised in the light engine were different. For further reference, the LED luminaires are labelled LED P and LED N, as illustrated in Figure 1. The technical specifications of the LED samples under consideration as as shown in Table 1. As observed,

TABLE 1. Specifications of LED Luminaires under test.

Specification	LED P	LED N
Rated Lumen	1400 lm	1400 lm
Rated CCT	6000 K	6000 K
Type	LP-SMD LED	LP-SMD LED
Number of LEDs	64	64
Parallel × Series	4×16	4×16
Input (AC)	230 V, 50 Hz	230 V, 50 Hz
Rated Power	15 W	15 W
Current (DC)	0.25 A	0.25 A

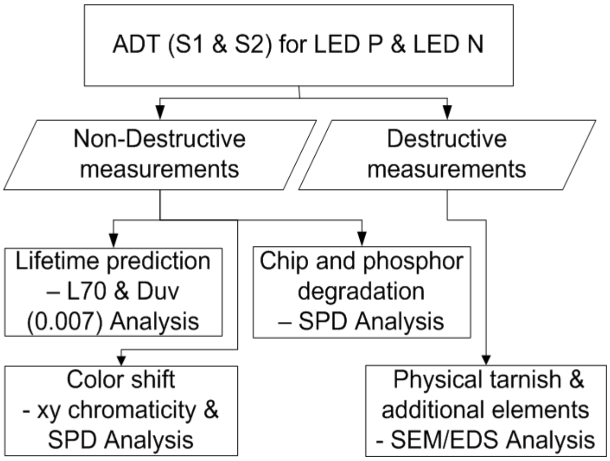

FIGURE 2. The methodology flow chart adopted for experimentation and analysis.

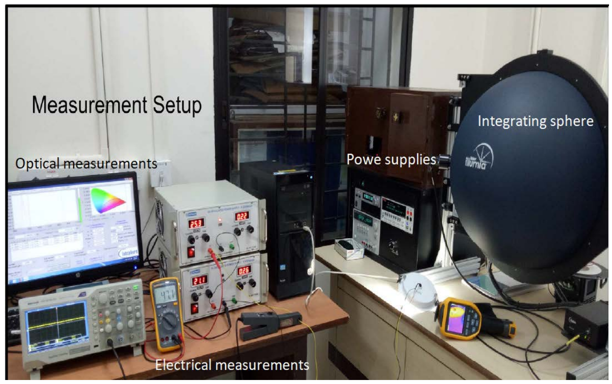

FIGURE 3. The experimentation set-up for ADTS1/ADTS2 conditions.

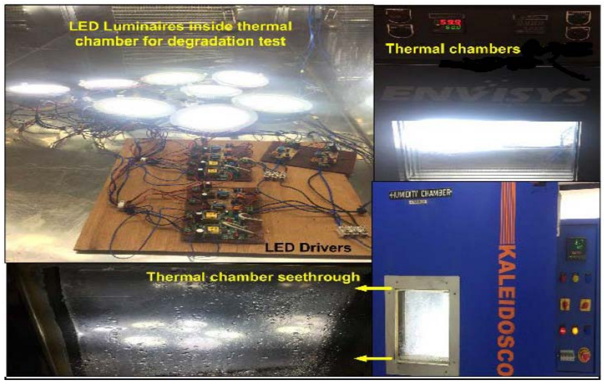

FIGURE 4. The electrical and optical characteristics measurement set-up during ADTS1/ADTS2 conditions.

both LED luminaires have similar electrical and optical characteristics and are used in recess mounted general illumination applications.

The figure 2 depicts the flowchart that corresponds to the performance analysis. To calculate lumen-based life prediction in terms of L70 [1], and Duv for colour-based life estimation, the experimental results from ADTS1 and ADTS2 are submitted to data analysis and modelling. Duv's mathematical model is established, and a limit of $\pm$ 0.007 is imposed in accordance with general lighting requirements. In addition to the colour shift, other performance suggestive signs like variations in the xy chromaticity colour space and differences in spectral power distribution curves are investigated. The LEDs are meticulously de-constructed to disclose the internal arrangements and expose the crucial components, with scanning electron microscopy (SEM) and energy dispersion spectroscopy (EDS) examination indicating the typical changes resulting in severe degradation.

The experimentation set-up is developed for two accelerated conditions and the LED luminaire samples under the study are placed inside the thermal humidity chamber and operated continuously under the accelerated condition as shown in Figure 3. The optical and electrical measurements are taken at regular intervals of time to observe the variations in the performance characteristics. The electrical parameters are measured with help of multimeter and oscilloscope, and the optical characteristics such as lumen, xy color coordinates, Duv and SPD are obtained from integrating sphere set-up as shown in Figure 4. After the degradation testing, the LED luminaire lifetime performance analysis is performed and lifetime is estimated from the experimental data obtained under ADTS1 and ADTS2 conditions.

III. RESULTS AND DISCUSSIONS

A. LUMEN OUTPUT ANALYSIS

The light output measurement data at various intervals is modelled using an IES-LM-80 generalized exponential model for lumen maintenance, which is given by equation (1).

$$L = \alpha \times e^{(-\beta \times t)} \tag{1}$$

L is the normalized lumen-maintenance, t is time in hours, α and β are model coefficients. The estimated lumen degradation profile along with the experimental data profile is shown in Figure 5.a and 5.b for LED P under ADTS1 and ADTS2 test conditions respectively. On similar lines Figure 5.c and 5.d are lumen degradation curevs for LED N under ADTS1 and ADTS2 test conditions respectively. As shown in Figure 5, LED N has a longer lifetime under ADTS1 and ADTS2 than LED P. The, LED N has a L70 lifespan that is $\approx$ 2.38 times that of LED P under ADTS1, while the lifetime of LED N is $\approx$1.43 times that of LED P under ADTS2. The reason for this is the physical structure of the LED and the Silver(Ag) mirror inside it. The role of

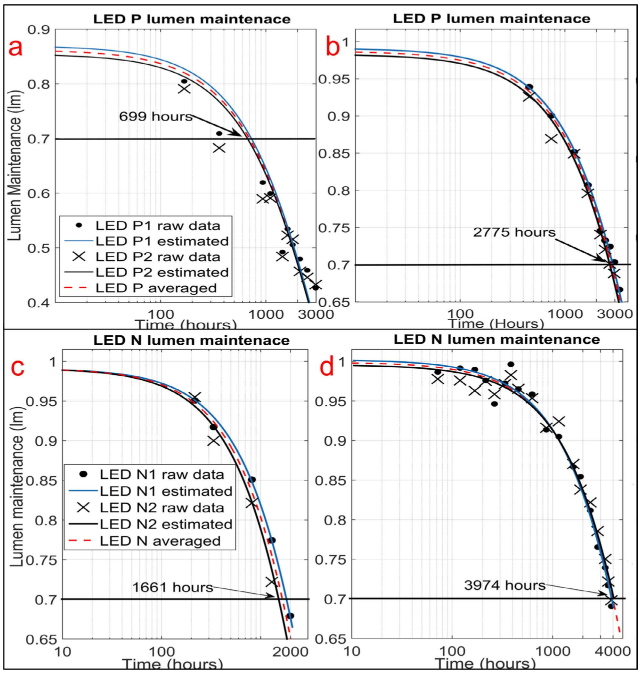

FIGURE 5. LED P (5.a and 5.b) and LED N (5.c and 5.d) lumen maintenance for ADTS1 and ADTS2.

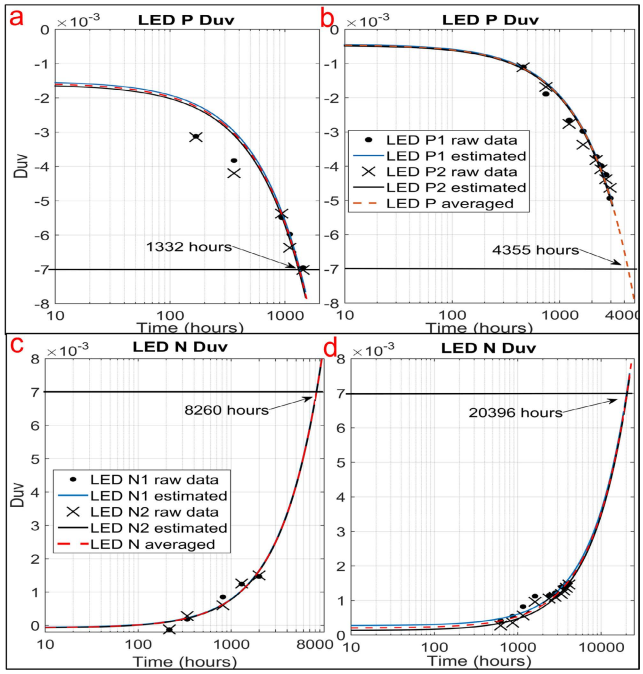

FIGURE 6. LED P (6.a and 6.b) and LED N (6.c and 6.d) Duv for ADTS1 and ADTS2.

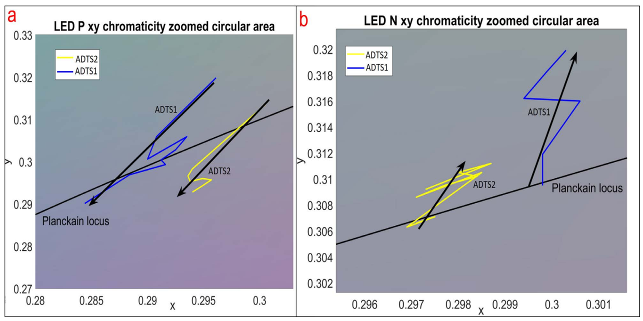

FIGURE 7. Xy chromaticity shift for LED P(7.a) and LED N (7.b) under ADTS1 and ADTS2 respectively.

Ag mirror in LED lumen degradation is further addressed in section III-C describing the LED package level analysis.

B. COLOUR CONSISTENCY ANALYSIS

1) DUV ANALYSIS

The *Duv* data from experimentation is analyzed to determine the model to depict the best model for the degradation profile using the curve fitting technique. The linear model is found to represent the experimental data the best with an R-square value $\geq$ 0.9, and the model is shown in equation (2). The slope and intercept coefficients of the model are M and N, respectively, and time is represented in hours by t.

$$Duv = M \times t + N \tag{2}$$

The estimated degradation profile along with experimentally obtained profile for LED luminaires under the study are shown in Figure 6. The x-axis is taken as log scale of time, therefore the plots look non-linear for a liner model fit. Figure 6.a and 6.b corresponds to the Duv profiles of for ADTS1 and ADTS2 for P and Figure 6.c and 6.d corresponds to the Duv profiles of for ADTS1 and ADTS2 for N respectively.

It is observed that the LED P *Duv* changed towards negative value, while LED N *Duv* is changed towards positive value. The positive and negative values of Duv represent the colour shift being opposite from each other and indicates the LED package variations under ADTS1/ADTS2, making it change the colour-based characteristics behaviour. For ADTS1 and ADTS2 degradation testing, the LED N Duv based lifetime is ≈4.7 and ≈6.2 times greater than the LED P luminaire, as shown in Figure 6.

2) XY CHROMATICITY ANALYSIS

The variations in the *xy*-chromaticity coordinate profiles of the LED P and of LED N, under the ADTS1 and ADTS2 conditions are shown in Figure 7.a and Figure 7.b respectively. It is observed that LED P colour variations are closing near the blue region passing through the Planckian locus; this indicates phosphor degradation, thereby reducing the ability of LED to convert blue to white colour. However, on analysis of deviations for LED N, the xy chromaticity shift is towards the green-red region above the Planckian locus. This indicates a lesser blue component in the converted white light and can be reasoned with blue-chip degradation dominance in addition to possible phosphor degradation.

3) SPD ANALYSIS

SPD is the deterministic parameter responsible for quantifying all the visual performance indicators of any light source [25]. The SPD profiles of the LED P and LED N before

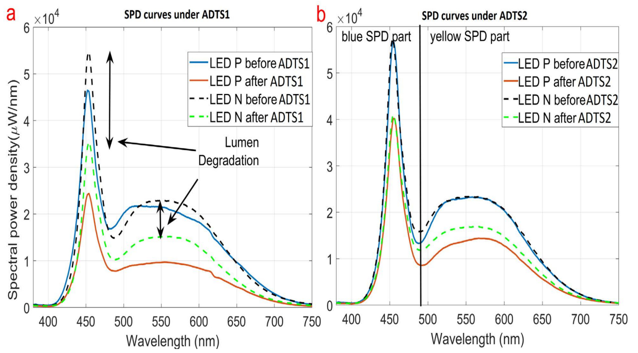

FIGURE 8. SPD analysis for LED P (8.a) and LEd N(8.b) under ADTS1 and ADTS2.

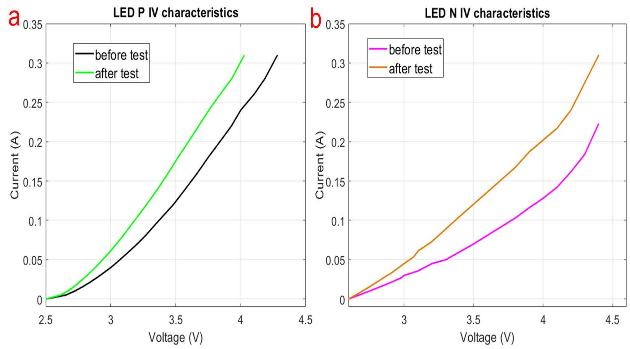

FIGURE 9. VI characteristics of LED P (9.a) and LED N (9.b) under ADTS1 and ADTS2.

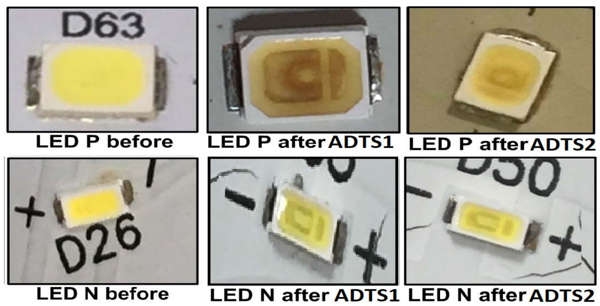

FIGURE 10. Discolouration of LED packages before and after deterioration testing.

TABLE 2. % degradation of blue and yellow area; and the B/Y area ratio in SPD.

	% Reduction B and Y area				B/Y area ratio			
	ADTS1		ADTS2		ADTS1		ADTS2	
LED	% B	% Y	% B	% Y	before	after	before	After
P	45.92	54.86	28.41	39.43	0.55	0.66	0.55	0.65
N	28.62	28.12	33.78	32.01	0.58	0.57	0.56	0.54

and post the degradation tests considered for the analysis are shown in Figure 8.a and Figure 8.b respectively. The optical power amplitude of all LED luminaires has decreased dramatically after the deterioration test compared to the start of the experiment, indicating serious lumen depreciation. For analysis, the SPD curve can be divided into two evident Gaussian regions: the blue part with the dominant peak wavelength of ≈ 450 nm and the yellow part with the dominant peak wavelength ≈ 550 nm. The proportional reduction in the area of the yellow region and blue region from the SPD is determined. It has been observed that, on average, the yellow part reduced by 39.43% (if initial is 100% after test, reduced to 60.75%) and in contrast, the blue amount area decreased by 28.41% for LED P. The observations for all the conditions are shown in Table 2. The results of LED P clearly indicate that the content of blue in white light after degradation is less than the amount of blue component in white light before degradation, showing the dominance of phosphor degradation. Likewise, the results of LED N suggest that the blue part degraded marginally more than the yellow region, which is why the claim of blue-chip degradation dominance to yellow phosphor degradation resulted in relatively lesser blue components in the degraded LED N luminaires. In addition to the area analysis, the B/Y ratio is analyzed to quantify the failure mechanism dominance through SPD analysis, and the results are shown in Table 2. LED P shows the B/Y ratio more after completing both degradation tests than initially, thus indicating the consequences of phosphor degradation dominance. Similarly, on analysis for LED N, the B/Y ratio is more diminutive and comparable after completing both degradation tests than the beginning, suggesting LED chip degradation dominance over phosphor degradation resulting in corresponding variations in the white colour characteristics.

4) VI CHARACTERISTICS ANALYSIS

To verify the LED chip variations, the VI (voltage-current) characteristics of multiple samples of the fresh new LED and degraded LED samples are compared and are shown in Figure 9. The VI characteristics of LED P and LED N is shown in Figure 9.a and Figure 9.b respectively. With the increase in junction temperature, the LED thermal resistance varies, thereby influencing the chip degradation resulting in a shift in voltage towards the lower-side for a particular current. The VI characteristics contributions to thermal resistance variations resulting degradation are also verified in [26]. As observed, the shift in VI characteristics indicates blue-chip degradation, which is relatively observed to be severe in LED N compared to LED P.

C. LED PACKAGE ANALYSIS

The identification of failure modes in the LED package resulting in severe lumen degradation and colour-based degradation is performed by observing physical and chemical characteristics signature changes inside the LED package. Through visual observations, it is identified that the LEDs that are aged have a very distinctive black/brown patina and a darker shaded yellow colour of phosphor as shown in Figure 10 from the single LED inspection of LED luminaires. Discolouration of the yellow phosphor is considered as the reason for colour shift. However, the LED package is de-constructed to reveal the *Ag* reactive mirror and the phosphor substrate for additional analysis, as illustrated in figure 11. The SEM analysis revealed a dark-coloured layer

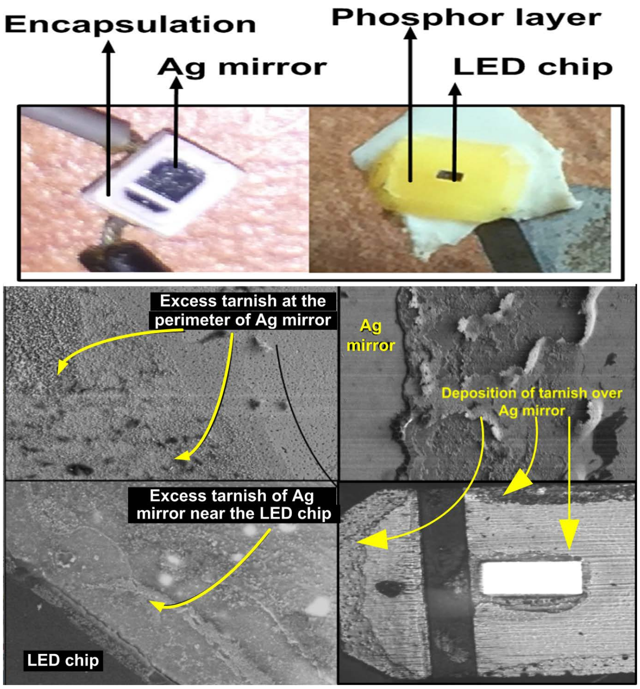

FIGURE 11. After the degradation test, the tarnish observed on *Ag* LED mirror.

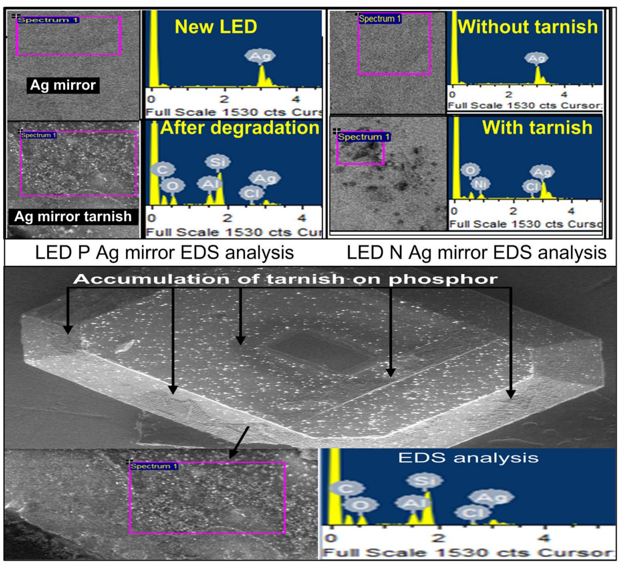

FIGURE 12. SEM-EDS investigation of LED *Ag* mirror tarnish following degradation test.

of material deposition on the *Ag* mirror due to the chemical reaction of the *Ag* mirror surface at high-temperature conditions. This tarnish is the by-product deposition and will now prevent the photons of blue light from reflecting to and through the phosphor, thereby compromising the LED light output. The SEM-EDS outcome is studied to reveal the internal variations in the LED Package structure and is reported in Figure 12. The observations showed the additional layer on the surface of the *Ag*-mirror at the peripheral of the package and the LED chip perimeter. The accumulation of tarnish around and on the chip also alter the LED chip performance. The observation of the underneath of the phosphor layer shows tarnishes spread, which also reasons with colour-based variations caused in the LED luminaires. The EDS study in Figure 12 identifies additional elements such as Chlorine (Cl) and Sulphur (S), which are expected to erode the *Ag* mirror due to the oxidation process at higher temperature conditions. The elements Cl and S are the possible residues during the LED packaging and lead frame attachment process. They remain dormant and gets activated to react with *Ag* at an elevated junction temperature of the LEDs and results in tarnish in due time, forming a mechanism for LED luminaire failure.

IV. CONCLUSION

The life of LED luminaires and their role in the light engine are investigated experimentally, with a focus on lumen and colour-based performance evaluations. According to the investigation, LED N-based luminaires have a less degradation than the lifetime of LED P-based luminaires for L70 and thus the lifetime of LED N luminaire is significantly more. In colour consistency-based applications, LED selection becomes even more important. As can be seen, LED N-based luminaires shifted away from blue and had a four-fold longer lifetime than LED P-based luminaires that shifted toward blue. The *Ag* mirror tarnish of the LED package is the primary cause of brightness decline. LED chip level deterioration or yellow phosphor degradation can both dominate colour-based degradation. It can be suggested that the LED manufacturers can perform the degradation test and the corresponding analysis of the characteristics features to identify the primary failure mechanisms and provide a lifetime performance analysis in the LED data-sheet. This, if included in the LED luminaire data-sheet with all the specifications by LED luminaire manufacturers, will allow consumers to see specifics about luminosity and colour-based changes as a product data-sheet, making it easier for them to choose appropriate luminaires for their needs. The findings pave the way for further study into defining the optimal internal LED features for overcoming *Ag* tarnish, blue chip, and phosphor-based degradation, and so improving the overall lifetime performance of LED luminaires as a system. Another scope for future work is improvement in the prediction of the lifetime performance. The prediction of lumen maintenance, color characteristics, SPD, etc., can be further improved by using the neural network, stochastic or advanced machine learning approaches. Thus, a system level lifetime performance characteristics prediction and analysis is presented and failure mechanisms at LED package level are identified and reliability of LED luminaire is estimated.

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