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EXPERIMENTAL STUDY OF WINDOWPANE'S ATMOSPHERIC PARTICULATE ACCOMULATION ON DAYLIGHT TRANSMITION

ESTUDIO EXPERIMENTAL DE LA ACUMULACIÓN DE PARTÍCULAS ATMOSFÉRICAS DE CRISTALES EN LA TRANSMISIÓN DE LUZ DIURNA

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ABSTRACT

Daylight is one of the most significant light source which could illuminate interior spaces by passing through windows and light collectors. Dust and aerosol accumulation on windowpanes reduce the light amount passing through it. The main objective of this research is to determine the impact of airborne particulate matters deposition on past light quantity. In this experiment the most prevalent particulate matters such as dust, carbon, and a mixture of both examined with 3 mm common commercial glasses at single and double glaze windowpanes and several interesting observations have been obtained. The result of this experiment will help building owners to adjust a window-cleaning schedule to reduce their lighting electricity consumption and expenses.

Keywords: Dust accumulation; Daylight; Windowpanes; Light transmission; Buildings.

RESUMEN

La luz del día es una de las fuentes de luz más importantes que podría iluminar los espacios interiores al pasar a través de ventanas y colectores de luz. La acumulación de polvo y aerosoles en los cristales de las ventanas reduce la cantidad de luz que pasa a través de ellos. El objetivo principal de esta investigación es determinar el impacto de la deposición de partículas en el aire sobre la cantidad de luz pasada. En este experimento, se obtuvieron las partículas más prevalentes, como el polvo, el carbono y una mezcla de ambos examinados con vidrios comerciales comunes de 3 mm en cristales de vidrios simples y dobles y se obtuvieron varias observaciones interesantes. El resultado de este experimento ayudará a los propietarios de edificios a ajustar un programa de limpieza de ventanas para reducir el consumo y los gastos de electricidad de iluminación.

Palabras claves: Acumulación de polvo; Luz del día; Cristales de las ventanas; Transmision de luz; Edificios.

1. INTRODUCTION

Nowadays, using daylight to illumine indoor spaces in order to reduce electricity consumption used for lighting is an interesting research topic (Hyunjoo et al., 2010; Han et al., 2010; Dubois et al., 2011; Frederick et al., 1985; Fawaz et al., 2006; Danny et al., 2010; Askar et al., 2001; Lorenz et al., 2001; Christian et al., 2008) .Many experts and architectures are working on approaches to transfer daylight into interior spaces by using optical fibers, wide windows, light collectors, etc. These light transformers always deal with some problems such as low translucency of light path and particulate matters (PM) accumulation on light entrance which caused by several mechanisms such as sticky surface, gravity assisted settlement, trapped particulates in rough surfaces etc. Dust accumulation on surfaces of windowpanes is a prevalent phenomenon which is influenced by both environmental and weather conditions. Dust and pollutant deposition on photovoltaic (PV) panels and its effects have been the main subject for many article since 1940 (Hamdy et al., 2006; Monto et al., 2010; Ahmad et al., 1998; kaldellis et al., 2011; Ibrahim , 2011; Hee et al., 2012; Shaharin et al., 2011). Many factors including particle sizes and matters (Shobokshy et al., 1993), surface characteristics (Hamdy et al., 2006; Hee et al., 2012) surface tilt angles (Hamdy et al., 2006), region conditions and time situations (Hamdy et al., 2006) have been investigated. All these investigations have been performed on PV modules and solar collectors (Said,1990) while other surfaces exposed to dust settlement including windowpanes have been ignored. This ignorance which may be caused by the similarity between PV transparent cover surface and glass, cease extra investigations on windowpanes, whereas they have shown some essential differences. Ekuakille et.al. (2016) investigates the impact of dust accumulation on photovoltaic solar modules in Baghdad city in Iraq. Their experiment showed that, deposition of the dust on the surface of the photovoltaic solar modules showed a reduction in both the short circuit current (Isc) and the output power compared to the same parameters of the clean module. Dastoori et.al. (2016) analysed the effect of accumulated dust particles' charge on PV module performance. their experimental results showed that charge level of accumulated dust particles on PV module's have significant impact on its output and dust particle accumulations are not associated with panel tilt angle. Subjects such as dust properties and illuminated light could be some of the same instances while some items like dust-settling regime, glass tilt angles, glass thickness, glass properties and passing light quality differs. In addition, many experts in PV modules consider only output electricity or system efficiency, while in this article, the light quantity and quality after passing the dirty glass and its influence on indoor spaces light have been take in to acount. Likewise, many of these investigations on PV modules performed in hot, arid and vulnerable to dust settlement countries such as Kuwait (Ahmad et al., 1998) and especially Egypt (Ibrahim , 2011) , whereas the windowpanes dirtiness is a ubiquitous phenomenon all over the world. Dust-settling regime is a complex phenomenon which have been investigated by many researchers. This complexity which comes from the exotic nature of dust property makes this phenomenon hard to comprehend. The dispensed dust in the air has many sources such as dust carried by wind, pedestrian and vehicular movement, pollution (carbon particles released from cars and industrial regions) and microfibers from fabrics (e.g. clothes, carpets) that are omnipresent everywhere, especially in interior spaces and easily scattered and settled as dust (Monto et al., 2010). Also dust-settlement characteristics on windowpanes like on PV modules or solar collectors influenced by local environment (weather condition, ambient temperature and humidity, nature of prevalent human activities, vegetation type, surface finishes, orientation and height of installation) and dust properties (type-chemical, electrostatic Property, size, shape and weight) which these two factors affect each other simultaneously and aggravate dust-settling (Monto et al., 2010). Additionally, the glass surface is also a paramount factor in dust settling. Glass sticky surface (furry, rough, adhesive residues, electrostatic buildup, untreated surfaces onward vulnerable to attract dews and drops) attracts more dust on its surface (Monto et al., 2010). Likewise considering gravity, inclined glass surfaces are more amenable to dust settlement; however, this matter is entirely influenced by weather conditions and wind prevalent direction and speed . Low-speed winds accumulate more dust on inclined glass surfaces in comparison with high-speed winds which dispel dust from it and also dust dispersal relates to dust property (weight, size, type) directly . Particularly, it is understood that an initial dust settlement on surface attracts more dust and pollutant afterwards (Monto et al., 2010).

However, dust particles sizes on windowpanes or PV modules are below than 500 μm (Monto et al., 2010), but dust particles sizes are so critical to light absorption (Shobokshy et al., 1993) . Regions near desserts experienced sandstorms and therefore sand accumulation but some regions near dry plains get involve with dust accumulations. Ahmad y. Al-Hasan (Ahmad et al., 1998) presents mathematical correlation for direct beam solar radiation for sand accumulation on PV modules in regard with dust deposition density, size and transmission coefficient, but his method to scatter the sand dust on samples is quite different with our method. Also El-Shobokshy MS and Hussein FM (Shobokshy et al., 1993) investigate reducing solar intensity with dust size on PV modules experimentally. Beside dust and sand accumulation, carbon and other PM deposition on windowpanes is very common in industrial areas and pollutant cities. Growth in carbon emissions in past years affect carbon settling on windowpanes by increasing its rate. Many residential regions like cities near industrial zones or areas with so much vehicular movements due to their high pollutant particles in air, nowadays are so vulnerable to carbon settlement on windowpanes. In this research, in addition to dust, the impact of carbon settlement on windowpanes considered precisely.

Common vertical installation of windowpanes in buildings mitigates the effects of dust settlement due to gravity forces; however, the effects of sticky surface which examined in this experiment remains almost constant. In sticky surface dust settlement mechanism, dust and pollutant in the air solute or stick in condensed water or other viscid elements on glass and after solidification makes a layer on it which is called dirtiness generally (Fig.1). Sticky surface of condensed water occurs when the glass surface have lower temperature than outside wet bulb temperature (Tw) or during night time when air expose to lose its moister content because of ambient temperature reduction. Based on drop or layer dew condensation structure on glass which is extremely contribute to surface characteristics and glass coated materials, the dust layer may expose different textures. Anna Werner and Arne Roos (2007) discern surface effects and coatings on condensation forms and amounts practically. Due to condensation type, PM density in sticky matters and dust constituents, the cover layer intercepts different amounts of light. miscellaneous dust ingredients, dissolvable minerals ratio and their types cause difference in dust deposition residues on windows (Monto et al., 2010) which after sticking or dissolving in condensed water or other viscid elements, coagulated cover layer causes different restriction on light path consequently different passing light quality and quantity. El-Shobokshy MS and Hussein FM (Shobokshy et al., 1993) analyzed different minerals like limestone, carbon and cement depositions on reduction in solar intensity on PV modules.

Figure1. A dirty window because of sticky surface dust settling mechanism. Stains established by coagulated dirty water drops.

Drizzles in rainy seasons especially at the beginning of autumn or spring, while wind, sand and dust storms are common also cause an accumulation of dust on windowpanes. The falling rain drops solute airborne particulate in itself, deliver it to the ground making a pellucid sky landscape after rain. These drops after coagulating on glass surface make mentioned dirtiness layer consequently, prevents passing daylight through it. In addition, the rain amount also influences dust deposition. Light rain pile up much deposition on glasses because they do not wash the glass exterior surface and just scatter the drops on them while heavy rain can drift the glass exterior surface dust deposition. The main issue in dust settlement due to condensation phenomenon on windowpanes is the glass kinds and their features. Glasses with low overall heat transfer coefficient (U) transfer less heat from separated spaces which cause lower condensation rate on outer surface when indoor spaces are cooler consequently less PM deposition rate on the windowpanes. G. weir and T. munner (1998) investigate double glazed windows and their U-values with different inert filled gas cavities like air and some noble gases which in their experiment xenon has minimum U-value at 8mm cavity. Coated surface with TiO_2 and SnO_2 also affect condensation and dust deposition. Additionally, surface treated glasses such as self-cleaning or anti-condensation glasses can attract few dew or dust on their surfaces (Fig.2). In addition, glasses with reflection coatings materials increase reflected light but causes less passing light. Also rough glass surface like a textured glass is more vulnerable to dust settlement in contrast with a smooth glass but this issue has not been tested in this works.

Figure2. Two different type of glass. Left one simple glass with no coatings and the right one, anti-condensation glass. More dew condensation easily observed on left glass. Image taken under courtesy of Pilkington anti-condensation glass industry.

Table 1. The environment lux amount at different conditions .

Weather conditions	Direct sunlight	Full daylight (not direct sun)	Overcast day	Very dark day overcast day	Full moon on a clear night	Moonless, clear night sky with airglow	Moonless, overcast night sky (starlight)
Luminance (lux)	130000	10000-25000	1000	100	0.267	0.002	0.0002

Many correlations such as transmission and absorption coefficient presented for quantitate amounts of translucency and transparency of an object. Eq. (1) shows Transmission coefficient percent (τ) and used for evaluation the experimental data obtained from this experiment. $I_\circ$ Is the light luminance entered the glass sample and I is the light luminance departed from the other side. Eq. (2) is the absorbance coefficient (A) equation; however, it is not used to evaluate data.

$$\tau = (I/I_\circ) \times 100 \quad (1)$$

$$A = log\ (I_\circ/I) \quad (2)$$

2. METHODOLIOGY

In this experiment, a 3 mm common commercial transparent glass with no color and coating have been used. The sample glasses cut in pieces to fit into the apparatus fixture. The facing surface of the glass opposite to light source covered with sticky black tape to avoid light penetration and just an 15×15 mm rectangular area left for light passing (Fig. 3). This narrow rectangular area at center of the sample glass has chosen to concentrate our attention into a less area with low passing light luminance fluctuation.

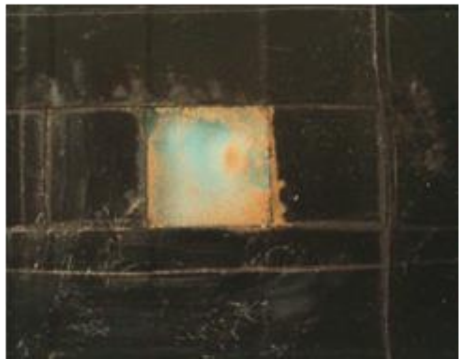

Figure 3. The glass sample with dust deposition. The glass central rectangular area is accumulating with dust and pollutants

For measuring luminance, a LEYBOLD DIDACTIC GMBH lux meter with 5 % error in measuring have been used. The experiments held in a quite dark lab to avoid disturbance environment light so lux meter indicates zero lux amount in the lab. Apparatus's light source is optical incandescent lamp with perfect output visible light spectrum simulates the natural daylight. Optical Light filters used against bare light to filtrate it in to five green, blue, red, yellow and purple colors to equipped us with different visible light wavelengths shown in table 3. These filters install on one side of the fixtures too and only passes a specific wavelength of bare light in the visible gamut of light spectrum (Fig.4).

Figure 4 : The scaled rail with glass fixtures.

Table 2 The interior spaces recommended minimum lux amount.

Space application	Courtroom, library-reading room, Office lit to 200 lux or more	Church, Public Hall, board room, library-	Entry Lobby, Farm Building, Office lit to 200 lux or less, Restaurant, Café, Bar	Musem, Gallery, Plant Room, Public Toilet	Circulation Space, Corridors, Service Locker Area, Staff Room
Recommended Minimum lux amount)	320	240	160	80	40-80

In this experiment, three different PM depositions dust, carbon and a mixture of both with equal mass ratio examined on glass with different density amounts. Specific amounts of dust and pollutants after weighting accurately dissolved in 50 ml distilled water affiliations. Link authors and affiliations using superscript lower case letters. A scaled rail holds the light source, the glass and filters fixture for both single glaze (SG) and double glaze (DG) conditions. The first glass fixture fixed on 250 mm distance from light source and the second glass fixture which take part in DG configuration fixed on 16 mm (0.62 inches) distance from the first glass fixture (Fig.4). The first fixture opposite side to light source holds light filtrates whereas the other side holds dirty glasses samples. In this experiment, the dirtiness of the second glass in DG configuration has not examined hence the second fixture just carries a clean glass. Naturally, for SG configuration, the second glass fixture uninstalls from the scaled rail. Dust used for this experiment to represent natural airborne particulate matters are obtained from screened clay to acquire dust with 75 µm particles dimension or less to simulate dust particles on windowpanes. Also to resemble man-made PM deposition on windowpanes, we use pure carbon with 50 µm particles dimension.

To obtain a homogenous solution. Then 1 ml of this solution dispersed on just 15×15 mm glass facing surface mentioned above (Fig.3) and heated to evaporate the water content. The residues remained on the glass surface afterwards form a deposition texture on glass, blocking light and resembling real PM deposition on windowpanes which caused by sticky surface phenomenon discussed above (Fig.1). Furthermore our method to disperse PM on the glass surface is far different from Ahmad y. Al-hasan (1998) method. Ahmad y. Al-hasan (1998) utilized a sand dust diffuser to sca tter sand dust on samples and then let them to settled by their own weight, whereas in this paper, the effect of sticky glass surface is examined. The initial bare and color lights luminance in 250 mm distance from light source, without any glass installation previously recorded by lux meter and demonstrated in figures. The color lights have lower lux amounts because they past firstly a light filter. In addition, the bare and color lights lux after passing a clean glass on the first fixture depicted in the figures as zero amounts. After preparing the dirty glasses models, the dirty glasses install on the first glass fixture against light source instead of clean one and the process of recording the past light lux continued for bare and color lights. In the next step after installing the second immaculate glass at 16 mm distance from first dirty sample glass the past light luminance recorded with the same procedure for DG condition as in SG configuration.

Table.3 .The filtrate past light wavelengths.

Filter color	green	Blue	Red	yellow	violet
Past light wavelength span	492-577	455-492	622-780	577-597	390-455

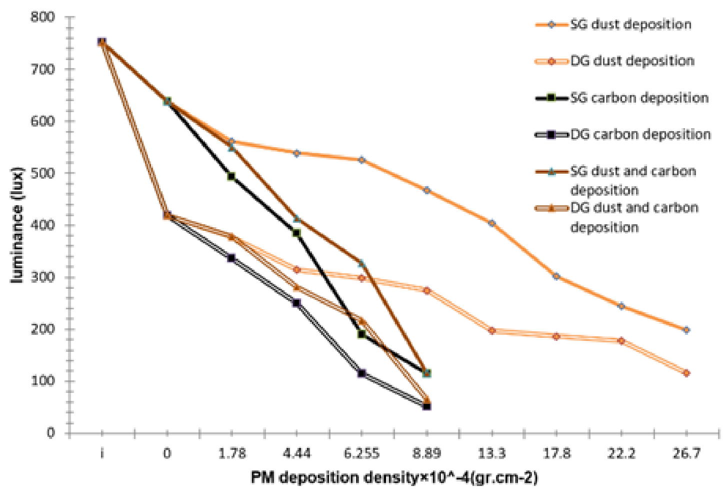

Figure 5. The luminance changes versus dust and pollutant settlement density for SG and DG glaze windowpanes.

3. RESULTS

The resulting effect of dust, carbon and mixture of both deposition on luminance for SG and DG windowpanes is shown in Fig. 5. As can be seen from this figure, the past light luminance decreasing continuously by increasing PM deposition density for SG and DG configurations. The i amounts on settlement density axis are related to initial light luminance before entering the first glass and zero points are related to light luminance after passing the clean glass. Zero points are lower than i points in SG windowpanes which confirm the fact that also clean glasses absorb light, which its amount is related to glass thickness, transparency and its structural characteristics. Likewise, more severe reduction in luminance between zero and i points in DG condition demonstrates that second clean glass affects light intensity extremely which makes PM accumulation phenomenon more adverse. A comparison between depositions apparently demonstrate that carbon depositions luminance reduction is much higher than other depositions and dust depositions have lowest reduction. Carbon and dust mixture depositions luminance reduction is almost average of other two depositions types, inherited from its constituents.
Figs. 6, 7 and 8 illustrate the transmission coefficient of bare and color lights for SG windowpanes accumulated with dust, carbon and a mixture of both respectively. The zero point on settlement density axis relates to clean glass transmission, which its transmission is about 84.91 % for 3 mm commercial glass used typically in houses windowpanes. It is obvious that glasses with same material but with higher thickness have lower transmission coefficient and therefore intensifies the effect of transmission subtraction, caused by PM settlement.
Fig. 6 depicts the transmission of glass samples covered with dust. The dust covered samples have higher transmission coefficient than other samples. Even at 0.00267 gr.cm^-2 dust density, transmission coefficient is higher than 0.000889 $gr.cm^{-2}$ density for other samples. In dust covered samples, the transmission coefficient of bare and color lights decreases continuously in regard with increasing dust deposition density. At low amounts of dust deposition the transmittance difference of bare and color lights are almost inferior to high dust depositions rates. At low amounts of dust density an order of purple, blue,

yellow, green, red and bare light transmission coefficient rate from high to low is recognizable however for high densities this order distorted. This distortion of bare and color light transmission affect the quality of daylight passing through windowpanes by deformation its wavelengths spectrum. In addition, bare and color lights transmission coefficient for dust covered samples at high amounts of dust deposition, densities shows sporadic manner that may be caused by different dust settlement texture on glass surface. Textures diversity in dust deposition samples contribute mainly to miscellaneous ingredients and heterogeneous size of dust particles.

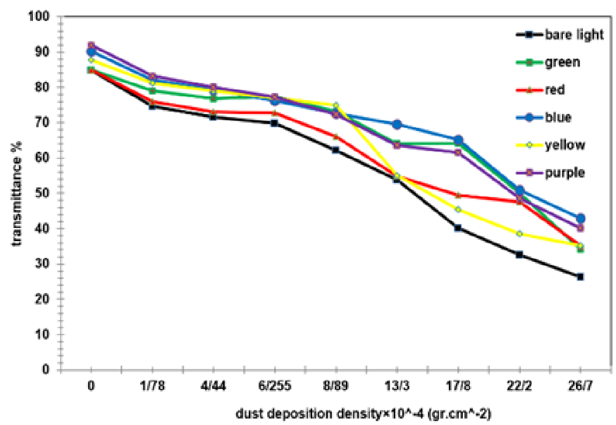

Figure 6 : The transmittance changes of SG windowpanes versus dust settlement density

By the way, the uneven texture of dust covered samples easily understands from Figs. 1 and 3. Ahmad y.Al-hasan (1998) investigated the transmission coefficient for various wavelengths in visible span for sand dust covered samples and demonstrate that difference in transmission coefficient is negligible, however in our method at high deposition densities it is not. Fig. 7 illustrates transmission coefficient of Carbon covered samples. These samples have lowest transmission among three other samples. In these samples transmission coefficient of color lights decreases almost evenly until 0.00044 gr.cm^{-2} carbon density, but after this point, drastic reduction in transmission coefficient experienced. However, the transmissions of carbon covered samples are different in colors and this causes light distortion but this difference is not so noticeable and could be neglected. Furthermore, the carbon covered samples transmission coefficient values show an anticipatable manner in contrast with dust-covered samples. This regular manner may be caused by more even carbon texture on glass samples than dust which this level surface developed by more homogenous infinitesimal particles of carbon than dust.

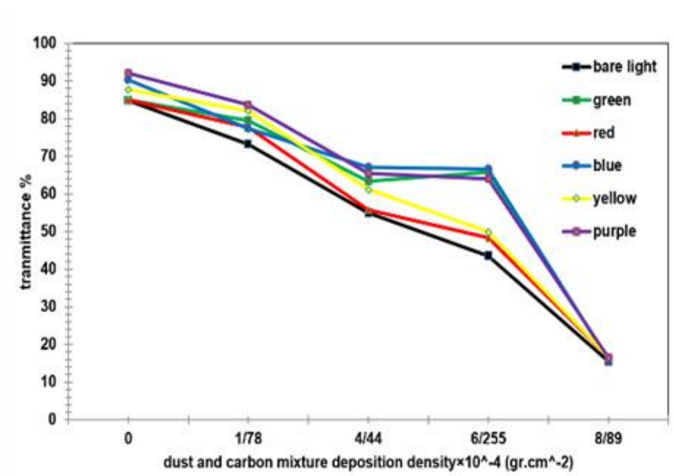

Figure 7. The transmittance changes of SG windowpanes versus carbon settlement density.

Fig. 8 illustrates transmission coefficient of dust and Carbon mixture covered samples. Carbon and dust mixture deposition have more transmission coefficient erratic manner than carbon-covered samples inherited it from its dust ingredient. In these samples, transmission coefficient decreases evenly until 0.000626 gr.cm-2 density but after this point, intense reduction observed. This abrupt reduction as we observed it in Fig .7 inherited from carbon part of the mixture but the dust portion lagged it to a higher amount of dust and carbon deposition density. In addition, these samples have higher transmission coefficient than carbon covered samples but it is not so considerable. A comparison between Figs. 6, 7 and 8 demonstrate that adding a tiny amount of carbon affects transmission severely. As the Figs. 7and 8 show the transmission of glass samples covered with pure carbon and a mixture of dust and pure carbon, at 0.000889 gr.cm2 pollutant density reaches 15.27 % and 15.45 % respectively when dust covered samples at 0.00267 gr.cm-2 density just reaches 26.4 %. This severe subtraction in transmission anticipated because the minuscule particles of carbon covers glass surface much better than dust and this better covering finally block more light. El-Shobokshy MS and Hussein FM (Shobokshy et al., 1993)also examined the effects of particle sizes on PV performance and reduction in light intensity, passing the PV modules transparent covers and reach same results.

Diversity in color light transmission in Figs 6, 7 and 8 distort the passing light spectrum. Dust, dust and carbon mixture, and carbon respectively have the highest passing light spectrum distortion. This distortion in dust deposition samples is very high and intensifies at high deposition densities may be cause of its heterogeneous ingredients. Also Carbon depositions has the lowest transmission fluctuations but dust and carbon mixture experienced some which inherited it from its dust constituents.

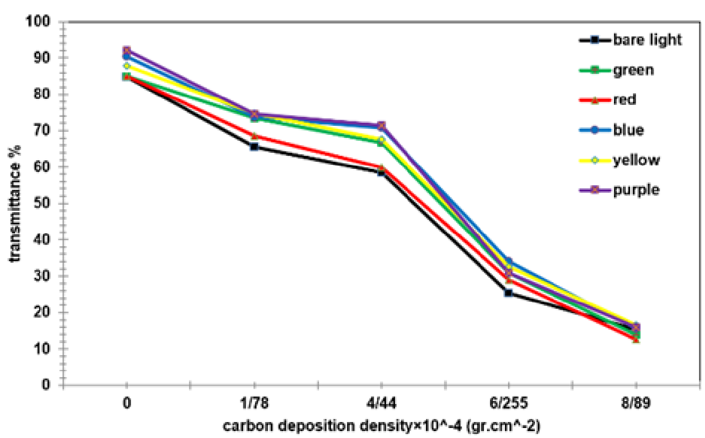

Figure 8. The transmittance changes of SG windowpanes versus dust and carbon mixture settlement density.

4. CONCLUSIONES

Contribute to illustrated diagrams, we easily concluded the transmission of windowpanes is thoroughly related to its cleanness and glass own transmission. Also it is understood that the influence of PM accumulation on windowpanes especially carbon type on passing daylight is more severe than we assumed. Therefore, the effect of carbon settlement on electricity consumption in pollutant cities and areas is more extreme and therefore it needs more precautions like windows cleaning. Furthermore, these precautions must be more restricted when utilized glasses are thicker or somehow vulnerable to the reduction of transmission or when windowpanes are double glazed. The negative effects of dust and pollutant deposition on glass transmission and electricity consumption initiate more secondary problems such as increasing demand in oil and other energy resource, higher greenhouse gases emission, etc. As PM accumulation on windows is a prevalent phenomenon, a scheduled cleaning program should be prepared to avoid extra load of electricity and energy consumption causes by low glass transmission like one we have for PV modules (Monto et al., 2010) based on building features and other factors discussed above. This program will help building owners to clean their windowpanes periodically to reduce the consequences of dirty windowpanes. Also using a lux meter in buildings could be beneficiary to determine the impact of dirty windows on the passing light. In addition, many other investigations should be conducted in other regions which deal with this problem to assess energy efficiency amounts accurately if windows keep cleaned regularly.

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