

Effects of increased solar ultraviolet radiation on materials

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Abstract

Synthetic polymers such as plastics, as well as naturally occurring polymer materials such as wood, are extensively used in building construction and other outdoor applications where they are routinely exposed to sunlight. The UV-B content in sunlight is well known to affect adversely the mechanical properties of these materials, limiting their useful life. Presently their outdoor lifetimes depend on the use of photostabilizers in the case of plastics and on protective surface coatings in the case of wood. Any increase in the solar UV-B content due to a partial ozone depletion would therefore tend to decrease the outdoor service life of these materials. It is the synergistic effect of increased UV radiation with other factors such as the temperature that would determine the extent of such reduction in service life. The increased cost associated with such a change would be felt unevenly across the globe. Those developing countries that depend on plastics as a prime material of construction and experience high ambient temperatures are likely to be particularly affected in spite of the relatively small fractional decrease in ozone at those locations. Assessment of the damage to materials, associated with ozone depletion, requires a knowledge of the wavelength dependence as well as the dose–response characteristics of the polymer degradation processes of interest. While the recent literature includes some reliable spectral sensitivity data, little dose–response information has been reported, so it is difficult to make such assessments reliably at the present time. This is particularly true for the naturally occurring materials popularly used in construction applications. To maintain polymers at the same useful lifetime in spite of increased solar UV-B content, the amount of photostabilizers used in the formulations might be increased. This strategy assumes that conventional stabilizers will continue to be effective with the spectrally altered UV-B-enhanced solar radiation. While the present understanding of the degradation chemistry suggests the strategy to have merit, its effectiveness, in an altered solar radiation environment, has not been demonstrated for common polymers. The availability of these data is crucial for reliably estimating the cost of mitigating the increased damage to materials as a result of a possible partial depletion of the ozone layer using this approach. © 1998 UNEP. Published by Elsevier Science S.A. All rights reserved.

Keywords: Photostabilizers; Polymers; Ultraviolet-B radiation; Temperature; Ozone depletion; Photodegradation

1. Introduction

A wide variety of synthetic and naturally occurring high polymers absorb solar ultraviolet radiation and undergo photolytic, photo-oxidative, and thermo-oxidative reactions that result in the degradation of the material [1–3]. The degradation suffered by these materials can range from mere surface discoloration affecting the aesthetic appeal of a product to extensive loss of mechanical properties, which severely limits their performance. The deleterious effects of solar UV-B radiation in particular, on wood, paper, biopolymers, and polymers (plastics and rubber), are well known. The phenomenon is of special interest to the building industry, which relies on polymer building products that are routinely exposed

to sunlight during use. Most of the common polymers used in such applications contain photostabilizers to control photodamage and to ensure acceptable lifetimes under outdoor exposure conditions. In both the USA and Western Europe about 20–30% of the annual production of plastics resin is used by the building sector [4]. The use of plastics in building applications is popular in the developing world as well because of the low cost and the ease of use of plastics components compared to the conventional metal, glass, mortar, wood, and other materials. Plastics are used in other products such as outdoor furniture, fishing gear, and marine craft, which are also routinely used outdoors. Table 1 illustrates the diversity of products that fall into this category. A large body of research literature on polymers deals directly with the issue of increasing the useful lifetimes of such products under routine outdoor exposure conditions [3,5–7].

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Table 1
Plastics materials routinely exposed to solar UV radiation

Building applications	Plastic window and door frames, siding, mobile-home skirting, gutters and downspouts, conduits, cable covering, flooring, outdoor furniture. Exterior fascia and soffit [rigid PVC formulations] Membrane roofing, geomembranes, weather-stripping [plasticized PVC, EPDM rubber, other rubbers] Glazing, covers for lighting fixtures [polycarbonate and acrylics] Varnishes and coatings used to protect surfaces. Highway marking paints. Resins used in the repair of monuments
Agricultural applications	Irrigation hoses, pipes, netting [PE and PVC]. Tanks for storage of water [Unsaturated polyester, and PE] Mulch films and greenhouse films [PE and PVC]
Transportation	Automobile tires [rubber]. Plastics used in automobile, aircraft, and marine vessel construction [composite]
Other	Fishing nets, sails, outdoor temporary housing, outdoor furniture, fibers and textiles
Biopolymers	Wool, human hair, wood, chitinaceous materials

PE, polyethylene; PP, polypropylene; PVC, poly(vinyl chloride); EPDM, ethylene-propylene-diene monomer.

It is mainly the ultraviolet radiation in sunlight that presently determines the useful lifetime of even adequately photostabilized plastic products in outdoor applications. Any increase in the UV-B content in terrestrial solar radiation due to a partial depletion of the stratospheric ozone layer is therefore expected to have an impact on the outdoor lifetimes of this category of materials. The damage to polymers under exposure to UV-B radiation is generally intensity dependent. While the incremental increase in UV-B in solar radiation due to ozone depletion is expected to be small, the efficiency of polymer degradation processes at these wavelengths is generally high. Marginal increases in solar UV levels can therefore translate into a noticeable decrease in the service life of polymer products. In applications such as organic protective coatings, electrical cable jackets, and plastic fishing gear, premature failure of the material can involve significant indirect economic losses that greatly exceed the replacement cost of the polymer material. With these applications, it is not easy to estimate the magnitude of the losses consequent to increased UV in sunlight.

The severity of the ozone-layer depletion and the consequent enhancement of UV-B in terrestrial solar radiation is latitude dependent. Most depletion of the ozone layer occurs at the higher latitudes where the largest increases in the UV levels are expected. While the solar radiation environment at these locations may become harsher due to additional UV-B, most of them enjoy relatively moderate temperatures that slow down the degradation reactions of materials. The change in the ozone column at low latitudes is relatively small, but these regions presently experience high ambient temperatures as well as high solar UV-B insolation. The service life of plastics under such harsh conditions is reported to be dramatically reduced. For instance, the tensile strength of white poly(vinyl chloride), PVC, pipes exposed for 24 months in Dhahran (Saudi Arabia) decreased by 43%, while an exposure of the same duration in Florida resulted in only a 26% decrease in the property [8]. The combination of high ambient temperatures is responsible for the reduced lifetime of the product. Even a small increase in solar UV-B levels can dramatically accelerate the deterioration processes in locations where the ambient temperature is high. In the tropical

developing countries housing construction mostly relies on lumber and other plant materials, while the use of plastics is also on the increase. Plastics are also extensively used in irrigation, water distribution and run-off applications, water storage tank construction, fishing nets, and agricultural films. A decrease in the service lives of these items can have a serious socio-economic impact on the populations in these countries.

The crucial role of temperature in the weathering of polyethylenes was illustrated in a recent study on desert exposure of polyethylene films. Two sets of polyethylene film samples, one maintained at 25°C at all times in an air-cooled, UV-transparent enclosure, and the other left under the much higher ambient temperature, were exposed to sunlight outdoors. The air temperature varied in the range 26–36°C during the period of exposure. However, the surface temperature of plastics exposed to sunlight can be much higher (by as much as 60°C for common plastics depending on color and thickness) than that of the surrounding air due to heat build-up [9]. Fig. 1 shows the change in extensibility of the films

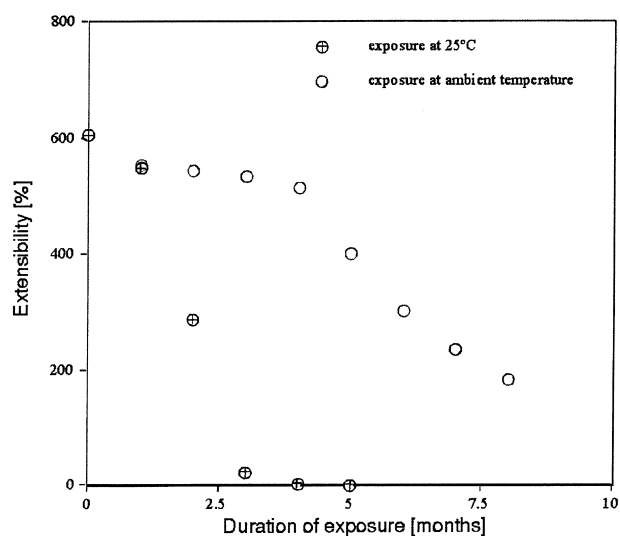


Fig. 1. Change in the extensibility of polyethylene film samples exposed in Dhahran, Saudi Arabia. The open symbols are for samples maintained at 45°C during the exposure, and the filled symbols are samples exposed under ambient conditions [12].

obtained for each set of samples. Samples kept at the lower temperature deteriorated much more slowly than those at ambient temperature although both were exposed to the same dose of solar UV radiation. It is the synergistic effect of high temperature and solar UV radiation that is responsible for the rapid degradation of the polyethylene films under these conditions. The findings are consistent with the observation that weathering rates of common plastics are very much slower when exposed floating in sea water in a marine environment, compared to those exposed on land [10]. Water acting as a heat sink is able to maintain low sample temperatures, retarding deterioration.

For a given material, the decrease in service life due to increased UV levels will invariably be determined by: (a) the spectral irradiance distribution of sunlight and environmental factors such as the ambient temperature; (b) the spectral sensitivity and the dose–response characteristics of the material; and (c) the efficacy of the available light stabilizers under spectrally altered light conditions [11]. Any serious assessment of the extent of anticipated photodamage requires quantitative information pertaining to each of these factors. The solar radiation data and the temperatures for most locations of interest are reliably known. A growing body of data on the spectral sensitivity of common polymers as well as some compounded systems used in specific applications (such as in PVC plastic siding) are becoming available [11]. However, the information on the dose–response characteristics of the degradation in plastics and natural materials, as well as on the effect of temperature on the UV-induced degradation, remains scant. Perhaps the least amount of information is available on the effectiveness of the conventional light stabilizers when used under UV-enhanced sunlight conditions. Fig. 2 shows the basic steps involved in photodamage and illustrates the various strategies commonly used to mitigate light-induced degradation of polymers.

Effective light absorbers such as benzotriazoles, benzophenones, and phenyl esters, as well as hindered amine light stabilizers (HALS), are presently used in plastics formulations intended for outdoor use (usually at a 0.05–2.0 wt.% level). Improved stabilizers are introduced into the market periodically. Reliance on increased concentrations of these conventional light stabilizers to maintain present service lifetimes of plastics products is the most likely response of the plastics industry to counter the effects of increased solar UV-B levels. Reported data, such as those for harsh desert weathering experiments, suggest that HALS and titania opacifier [13] used at higher levels can considerably increase the service life of common plastics. However, the potential of the conventional photostabilizers to breakdown under exposure to enhanced UV solar radiation, possibly decreasing their effectiveness, is a concern. Even some commercial HALS compounds are reported to be photolyzed by UV radiation [14], but no action spectra for the breakdown of even the common photostabilizers are available. Novel and more effective light stabilizers might be developed to supplement the existing compounds.

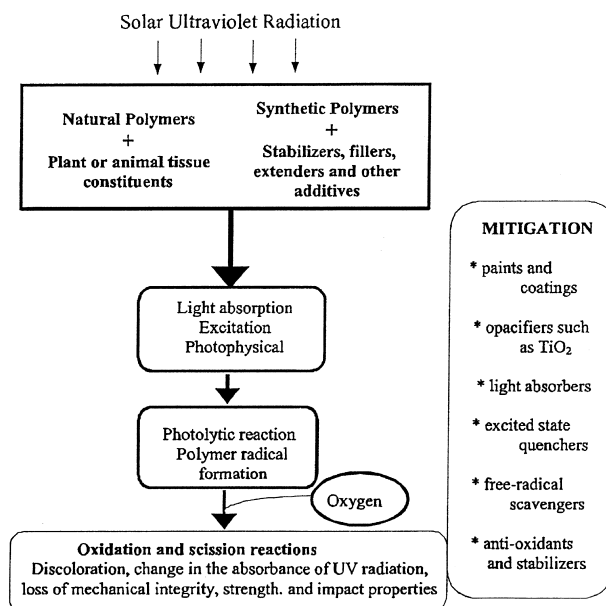


Fig. 2. Schematic diagram of the various stages of light-induced damage in polymers and its mitigation.

With organic light stabilizers such as hindered amines, increasing the stabilizer level in the composition will have little or no impact on processibility of the resin. The cost, however, will be significantly affected as the contribution of the stabilizer cost to the total cost of a product such as greenhouse films can be as much as 30%. With inorganic opacifiers such as titania or carbon used with resins such as PVC, for instance, higher levels will affect processibility, power consumption, and even the lifetime of processing equipment, due to increased melt viscosity. Capstock technology [15] where a photolabile polymer is covered by a surface cap layer of the same material rich in light stabilizer or a photoresistant polymer is also a promising approach. As the incremental cost of these efforts rises, it is possible that other weather-resistant polymers will become more cost-effective for particular high-value applications.

In the case of high-value wood, protective surface coating will remain the primary means of controlling light-induced damage. With low-quality material (which is generally left unprotected) used in dwelling construction in developing countries, a decrease in useful lifetime is expected. Use of wood in building might involve additional costs for more frequent painting or other maintenance.

2. UV damage to polymers

The chemical pathways by which common polymers photodegrade are fairly well known, but various aspects of the mechanisms involved remain unelucidated. However, it is important to take into account the very significant influence of compounding additives in modifying these pathways [16]. Typically, these are pigments, extenders, photostabilizers, and thermal stabilizers. For instance, the effect of flame-

retardant additives on the photodegradation of several common polymer compositions was reported recently [17–20]. Virtually all plastics products are manufactured using extrusion, injection molding, or extrusion blowing. The processing of polymers using heat and high shear into useful end products introduces impurities and reaction products that make them susceptible to photodegradation. Because of these complications, the extrapolation of research findings on UV-induced degradation of pure polymer resins to compounded and processed products of the same polymer is often unreliable. Photodegradation data generated on the actual polymer formulations used in practice, processed in the conventional manner, are the most useful for assessment of damage.

The many concurrent chemical processes taking place in polymers exposed to UV radiation result in several different modes of damage, each progressing at a different rate. It is usually the critical first-observed damage process that determines the useful service life of the product. For instance, poly(vinyl chloride), PVC, window frame exposed to sunlight undergoes discoloration, ‘chalking’, loss of impact strength, and a reduction in tensile properties as well as a host of other chemical changes. It is, however, the discoloration (or the uneven yellowing) of the window frame that generally determines its service life [21]. The consumer may demand its replacement based on this criterion alone. In most developing countries, however, these products often continue to be used despite changes in appearance or eventual stages of damage becoming apparent. With continued use, however, other damage such as ‘chalking’ and eventually loss of impact resistance (leading to cracking) can occur, making the product even more unacceptable. The two critical modes of photodamage applicable to most natural and synthetic materials are yellowing discoloration and loss in mechanical integrity.

2.1. Yellowing discoloration

Both natural biopolymer materials and synthetic polymers undergo UV-induced discoloration, usually an increase in the yellowness on exposure. Lignocellulosic materials such as wood and paper readily undergo light-induced yellowing [22]. While both cellulose and lignin constituents of wood can photoyellow, it is the latter that is mostly responsible for the phenomenon. Lignin, which comprises 29–33 wt.% of softwood, contains numerous chromophores that efficiently absorb UV radiation [23]. As much as 80–95% of the absorption coefficient of wood can be ascribed to the lignin fraction. The complex photochemistry of yellowing in lignin-containing materials is not completely understood; the present understanding of the process was succinctly summarized recently [24] and at least four pathways of photodamage have been recently discussed. The practical interest in discoloration relates specially to newsprint paper made of groundwood pulp that yellows rapidly on exposure to sunlight. Action spectra for photoyellowing of these pulps have been reported, and a recent study [25] confirms the solar UV wavelengths to cause yellowing, while the wavelengths in the region of

500–600 nm were shown to photobleach the pulp. The cellulose fraction in wood also undergoes a free-radical-mediated degradation on exposure to wavelengths less than 340 nm.

The photodamage to wool has serious economic implications in large producer countries. Exposure of wool keratins to sunlight is well known to cause yellowing, bleaching, and main-chain scission of the proteins [26]. Launer [27] established that visible radiation in sunlight causes photobleaching of wool, while the UV wavelength causes photoyellowing. Based on the data of Lennox et al. [26], the most effective yellowing wavelengths were in the UV-A region (340–420 nm). As ozone-layer depletion results in an increase in both UV-B as well as UV-A content of sunlight, wool appears to be a material that might be particularly affected.

Preliminary data on the photostability of chitosan, another commonly found biopolymer, were recently reported [28]. While not used commercially in high volume, the biopolymer occurs widely in nature in fungal cell walls, crustacean exoskeleton, and in insect tissue. Ultraviolet radiation in the wavelength range 250 to about 340 nm was reported to cause changes in the average molecular weight as determined by solution viscosity as well as the absorbance (at 310 nm) in chitosan derived from crab shells. The damaging role of UV-B in creating free radicals in human hair has also been reported [29], but no quantitative spectral sensitivity data are available.

Of the synthetic polymers, poly(vinyl chloride), PVC, is best known for its tendency to undergo photoyellowing. The photothermal mechanisms leading to the formation of conjugated polyenes that cause yellowing is well understood [30,31]. An opacifier (generally rutile titania) is used to slow down the rate of yellowing in white profiles widely used in siding, window frames, and pipes [32]. The reaction is localized in the surface layers of the polymer, especially in opaque formulations used in building applications. The activation energy for dehydrochlorination is reported to have a temperature coefficient of 8–18 kJ mol⁻¹, suggesting this process to be readily enhanced at high temperatures [33]. As with wool and paper, while the UV wavelengths cause yellowing of PVC the visible radiation at wavelengths above 400 nm tends to cause photobleaching. Several possible photobleaching mechanisms are reported in the literature, but the process is little understood.

A second polymer used in building applications, mainly as glazing, is polycarbonate. When irradiated with short-wavelength UV-B or UV-C radiation, polycarbonates undergo a rearrangement reaction (referred to as a photo-Fries rearrangement). At low oxygen levels this reaction can yield yellow-colored products such as *o*-dihydroxy-benzophenones [34]. But when irradiated at longer wavelengths (including solar visible wavelengths) in the presence of air, polycarbonates undergo oxidative reactions that result in the formation of other yellow products [35]. However, neither the detailed mechanisms nor the specific compounds responsible for the yellow coloration have been fully identified [36].

Monochromatic exposure experiments on the wavelength sensitivity of several degradation processes of bis-phenol A polycarbonates have been reported recently (see Table 2).

Polystyrene, widely used in both building and packaging as expanded foam, also undergoes light-induced yellowing. The presence of air retards the process and the origin of the coloration is again not clear. It is variously attributed to conjugated polyene, various oxygenated species, or products of ring-opening reactions [1].

2.2. Loss of mechanical integrity

The loss of strength, impact resistance, and mechanical integrity of plastics exposed to UV radiation is well known. These changes in bulk mechanical properties reflect polymer chain scission (and/or cross-linking) as a result of photodegradation. Changes in solution viscosity and the gel permeation characteristics of polymers have been used [18,19] to establish molecular changes during photodegradation.

With polyethylene and polypropylene, the loss of useful tensile properties on exposure to solar radiation is a particular concern. These materials are used extensively in agricultural mulch films, greenhouse films, plastic pipes, and outdoor furniture. Polyethylene films exposed to solar UV-B radiation readily lose their extensibility and strength [42,43] as well as their average molecular weight decreasing [44]. General features of the mechanism of photodegradation in both polyethylene and polypropylene are fairly well understood [1,45]. The mechanism is one of thermo-oxidative or photo-oxidative degradation rather than of direct photolysis, and is catalyzed by the presence of metal compounds. The free-radical pathways that lead to hydroperoxidation and consequent chain scission are fairly well understood [5]. Of the polymers used worldwide, polyethylene enjoys the largest

annual volume. Research interest in understanding and controlling the photodegradation process of this polymer is therefore continuing. Efficient classes of light stabilizers such as the HALS are used to ensure that adequate lifetimes are obtained in polyolefin products intended for outdoor use under a wide range of UV environments.

Poly(vinyl chloride), PVC, is used widely in building applications where the impact strength of the material is an important requirement. The projected consumption of PVC in the near future (1995–2010) is much higher in the developing world and in countries in transition. Estimated demand for Asia alone is more than that for the USA, Canada, and the European Community combined [46]. Exposure to solar UV radiation is well known to decrease the impact strength of the polymer [30]. As the surface layers of the plastic material degrade, the titanium dioxide powder used as an opacifier is gradually released and may even form a surface layer loose enough to be rubbed off. This is responsible for the ‘chalking’ of extensively exposed PVC siding materials. Both the tensile strength and the extensibility of rigid PVC samples also decrease with the duration of exposure to solar UV radiation and the material finally embrittles [30]. Similar changes also take place on exposure of plasticized PVC formulations used in membrane roofing applications and cable coverings [47].

Other common polymers shown in Table 1 also undergo a loss in mechanical strength on photodegradation. A rapid change in the mechanical integrity of polystyrene caused by extensive chain scission during the photodegradation has been reported [48].

3. Wavelength sensitivity of photodegradation

Assessing the damage to materials from exposure to UV-enhanced sunlight requires an understanding of their spectral

Table 2
Spectral sensitivity data from monochromatic exposure experiments

Material type	Damage studied	<i>B</i>	<i>r</i> ²	Ref.
1. Poly(vinyl chloride)				
1.1. Rigid compound	yellowing	−0.035	0.95	[37]
−0% TiO ₂		−0.048	0.99	
−2.5% TiO ₂		−0.058	0.98	
−5.0% TiO ₂		−0.073	0.99	
1.2. Plasticized compound	stiffness change	−0.02	0.83	[38]
2. Polycarbonate				
2.1. Rigid sheets	yellowing	−0.082	0.99	[39]
2.2. Films	quantum yield of chain scission	−0.044	0.99	[18]
	change in absorbance	−0.059	0.88	[40]
	quantum yield of chain scission	non linear		[41]
3. Poly(methyl methacrylate)				
4. Lignocellulose				
4.1. Mechanical pulp	yellowing	−0.011	0.99	[25]
5. Chitosan				
5.1. Chitosan films	absorbance at 310 nm (260–320 nm)	−0.017	0.89	[28]
	viscosity	non linear		
6. Wool	yellowing	−0.025	0.95	[26]

Note: *r* is the correlation coefficient.

sensitivity. Spectral sensitivity data for polymers are typically generated using a source of monochromatic radiation or a white-light source such as a filtered xenon source (one whose spectral irradiance distribution is designed to closely approximate that of terrestrial sunlight at unit air mass). With experiments based on exposure of materials to monochromatic radiation, the effectiveness $I(\lambda)$ in units of damage per incident photon (defined as the ratio of the measured change in the property of interest ΔP to the number of incident photons) is obtained for several irradiation wavelengths. In most instances a linear relationship exists between the logarithm of the effectiveness of damage and the wavelength of exposure, with higher damage per incident photon obtained at the shorter UV wavelengths. The gradient B of a plot of the natural logarithm of $I(\lambda)$ versus λ is a measure of the monochromatic wavelength sensitivity. Table 2 lists the values of B that quantify the wavelength sensitivity of polymeric materials reported in the literature. All data in the Table are based on laboratory exposure experiments using monochromatic radiation. The spectral sensitivity of a material assessed by this approach depends upon the type of damage process investigated.

When using a white-light source, a series of cut-on filters is used to isolate different bands of the source spectrum [11]. The increment of radiation between two adjacent filters in the series depends on their transmission spectra $T(\lambda)$ and the spectral irradiance distribution of the source $H(\lambda)$:

$$\text{Increment} = H(\lambda)[T_i(\lambda) - T_{i+1}(\lambda)]$$

Typically, the change in a property of interest (Δ Damage),

$$\text{Increment} = H(\lambda) (T_i(\lambda) - T_{i+1}(\lambda))$$

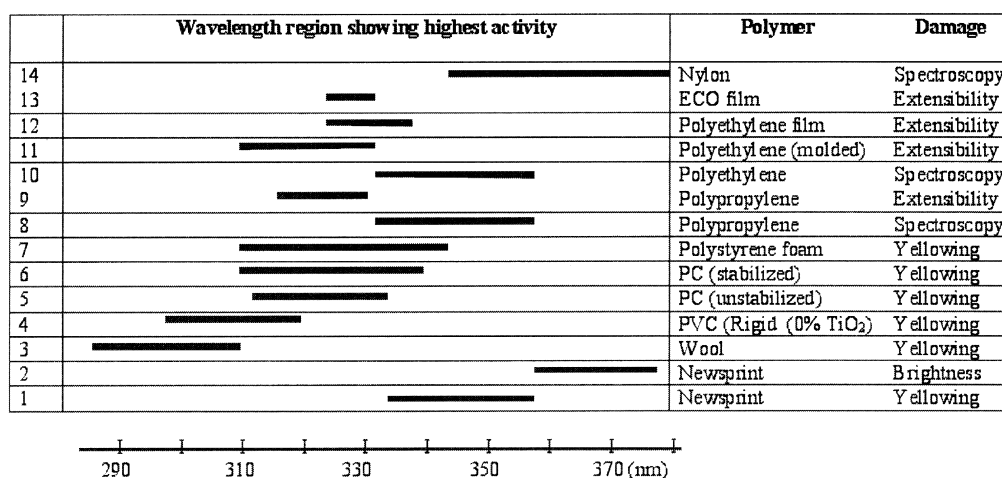


Fig. 3. Summary of activation spectra for common polymers exposed to solar-simulated radiation (filtered xenon source radiation) published in the literature showing the wavelength interval in which most photodamage was obtained. All data reported were generated using the cut-on filter technique. ECO, ethylene-carbon monoxide (1%) copolymer; PC, bisphenol A polycarbonate sheet; PVC, poly(vinyl chloride). 1, 2, Newspaper paper made of mechanical pulp from Southern Pine. Photodamage measured is the increase in yellowness index and the optical brightness of the paper [25]. 3, Data estimated from Ref. [27]. 4, Rigid PVC sample similar to that used in vinyl siding applications except that no opacifier (titanium dioxide) was used. The absence of the opacifier allowed photodamage to be obtained within a reasonable duration of laboratory exposure. The reference source includes data for samples formulated with opacifier as well [37]. 5, Data for yellowing of PC. The study also found cross-linking damage at wavelengths below 315 nm [49]. 6, Commercial PC containing a light absorber as a photostabilizer was used to obtain these data using natural sunlight as a source of radiation [25]. 7, Data for expanded extruded polystyrene sheets designed to photodegrade faster than regular resin [50]. 8, Data for polypropylene films [51]. 9, Injection-molded polypropylene [50]. 10–13, Data on polyethylene films [28]. 14, Nylon fibers [52].

before and after exposure of identical samples exposed behind filters i and $i + 1$, is obtained from the experiment. This is plotted as a function of the bandpass ($T_i(\lambda) - T_{i+1}(\lambda)$) at half bandwidth for each pair of filters used. The resulting bar diagram (see Fig. 3) has been referred to as an activation spectrum in the materials research literature. Wavelength sensitivity studies using a xenon source (which provides radiation spectrally similar to solar radiation [53]) are particularly valuable in assessing the potential effects of enhanced UV-B radiation in sunlight (Fig. 3). A qualitative estimate of the relative significance of various ultraviolet wavelengths in the terrestrial solar spectrum in causing specific photodamage in polymers can be discerned from the published activation spectra. Fig. 4 shows a compilation of these regions from published data on various polymers. With activation spectra for most polymers, it is the less efficient UV-A wavelengths rather than the UV-B wavelengths that yield the largest relative amount of photodamage. This is expected because of the relatively low UV-B content in the solar spectrum. However, in activation spectra for yellowing of PVC (rigid formulations), polycarbonate, and polyamide, the maximum damage is obtained in a spectral region that includes UV-B wavelengths as well. It is clear from Fig. 4 that most of the polymers will undergo considerable degradation when exposed to the UV-B and/or UV-A spectral regions, suggesting that any increase in the solar UV will result in an increase in damage.

The change in property of interest may also be plotted as a function of the 10% transmittance value of filters to yield a cumulative spectral sensitivity curve. Data on wavelength

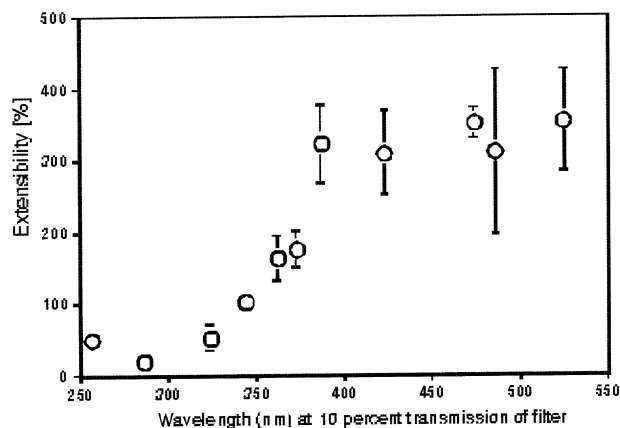


Fig. 4. Cumulative wavelength sensitivity curve for change in extensibility of low-density polyethylene film exposed to a filtered xenon source for 469 h at ambient temperature [54].

sensitivity of polyethylene film samples exposed to filtered xenon-source radiation are shown in Fig. 4. The data show that wavelengths shorter than about 400 nm affect the mechanical properties of the film. Using a full white-light spectrum as opposed to narrow near-monochromatic bands of radiation in wavelength sensitivity experiments has the advantage that synergism (or antagonism) at different wavelengths can contribute to the results.

The spectral sensitivity data from the two experimental approaches (using near-monochromatic radiation and using a white-light source) are interconvertible provided several assumptions are made: (i) the law of reciprocity applies; (ii) effects of different wavelengths are additive (the lack of synergistic or antagonistic effects); and (iii) the light absorbance characteristics of the polymer are not time dependent within the durations of exposure. Even for the common polymers often not enough data are available to validate these assumptions. However, in the case of poly(vinyl chloride), PVC, and mechanical pulp materials, the activation spectra have been used to derive monochromatic spectral sensitivity curves successfully in the UV-B and UV-A wavelength range [11].

4. Conclusions

The lack of reliable wavelength sensitivity data and dose–response information has always been a serious limitation in efforts to assess the increased damage to materials from enhanced UV levels resulting from ozone-layer depletion. In recent years, however, this need has been partly addressed with several relevant action spectra for at least the common polymeric materials reported in the literature. More importantly, some of these data pertain to formulations typically used in outdoor applications in the building industry. Also significant is the availability of spectral sensitivity data for several biopolymers during recent years.

However, very limited dose–response data are available for these same compositions and the information reported is

somewhat inconsistent. Furthermore, the effectiveness of photostabilizers (or even their own photostability under exposure to UV-enhanced solar radiation) still remains unclear. These limitations do not allow reliable damage estimates to be made for polymers typically used in building applications. The various assumptions typically employed in damage assessment for materials have not yet been validated for a great majority of polymers.

An important aspect of the problem is the role of temperature in exacerbating the effects of an increase in solar UV radiation. In regions with high ambient temperatures the assessment process must take into account the very high bulk temperatures polymers are subjected to during their service life. To do so effectively, a better understanding of UV-induced degradation processes at lower temperatures will be particularly useful. Again the data available on this topic are very limited.

While the relevant information is beginning to appear in the research literature, there are as yet inadequate data to conduct reliable damage estimates for most common polymers.

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