

5 Polyesters

5.1 Polyesters

Polyesters are formed by a condensation reaction that is very similar to the reaction used to make polyamide or nylons. A diacid and dialcohol are reacted to form the polyester with the elimination of water as shown in Fig. 5.1. The monomers of each polyester are described in each plastic section.

While the actual commercial route to making the polyesters may be more involved, the end result is the same polymeric structure. The diacid is usually aromatic. Polyester resins can be formulated to be brittle and hard, tough and resilient or soft and flexible. In combination with reinforcements such as glass fibers, they offer outstanding strength, a high strength-to-weight ratio, chemical resistance and other excellent mechanical properties. The three dominant materials in this plastics family are polycarbonate (PC), polyethylene terephthalate (PET) and polybutylene terephthalate (PBT). Thermoplastic polyesters are similar in properties to Nylon 6 and Nylon 66, but have lower water absorption and higher dimensional stability than the nylons.

Weathering: UV radiation absorbed by polyesters leads to scission (breaks in the polymer chains) reactions centered on the ester linkages as shown in Fig. 5.2. This leads to formation of small molecules such as carbon monoxide and carbon dioxide and polymer chains with hydroxyl, carboxyl and aldehyde end groups. Reaction of the radicals produced by photolysis with oxygen can produce chain scission and molecular weight reduction and carbonyl formation. Recombination of transient radicals can lead to cross-linking of the polymer. When water is present, hydrolysis occurs.

Stabilization¹: Polyesters are stabilized with:

- **UVA:** such as 2-hydroxy-4-octyloxybenzophenone and 2-(2H-benzotriazol-2-yl)-p-cresol
- **HALS:** such as 1,3,5-triazine-2,4,6-triamine, $N,N''[1,2\text{-ethane-diyl}\text{-bis}[[4,6\text{-bis[butyl}(1,2,6,6-pentamethyl-4-piperidinyl)amino]-1,3,5-triazine-2-yl]imino]\text{-}3,1\text{-propanediyl}]bis[N',N''\text{-dibutyl-}N,N''\text{-bis}(1,2,2,6,6-pentamethyl-4-piperidinyl)]$ (Chimassorb® 119 from Ciba/BASF)]
- **Screener:** carbon black, zinc oxide
- **Acid scavenger:** hydrotalcite
- **Phenolic antioxidants:** such as ethylene-bis(oxyethylene)-bis(3-(5-tert-butyl-4-hydroxy-m-tolyl)-propionate)
- **Phosphite:** such as bis-(2,4-di-t-butylphenol) pentaerythritol diphosphite
- **Optical brighteners:** such as 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazazole)

5.2 Liquid Crystalline Polymers

Liquid crystalline polymers (LCPs) are a relatively unique class of partially crystalline aromatic polyesters based on 4-hydroxybenzoic acid and related monomers shown in Fig. 5.3. LCPs are capable of forming regions of highly ordered structure while in the liquid phase. However, the degree of order is somewhat less than that of a regular solid crystal. Typically, LCPs have outstanding mechanical properties at high temperatures, excellent chemical resistance, inherent flame retardancy and good weatherability. Liquid crystal polymers come in a variety of forms from sinterable high temperature to injection-moldable compounds.

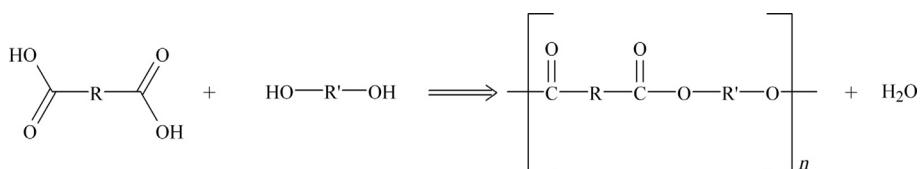
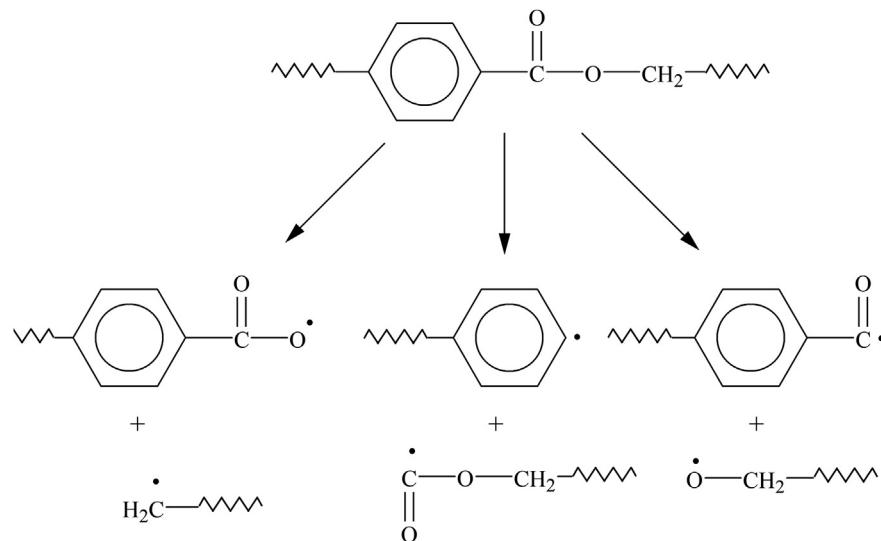


Figure 5.1 Chemical structure of polyester.

Figure 5.2 Photolysis of polyesters produces various radical species.



LCPs are exceptionally inert. They resist stress cracking in the presence of most chemicals at elevated temperatures, including aromatic or halogenated hydrocarbons, strong acids, bases, ketones and other aggressive industrial substances. Hydrolytic stability in boiling water is excellent. Environments that deteriorate these polymers are high-temperature steam, concentrated sulfuric acid and boiling caustic materials.

As an example, the structure of Ticona Vectra® A950 LCP is shown in Fig. 5.4.

Weathering Properties: LCP resins exhibit excellent mechanical property retention after exposure to weathering.²

After 2000 h of artificial weathering, moldings made from Vectra® retained more than 90% of their initial mechanical property values. After one year of outdoor weathering, a slight white deposit was detected. The white deposit is the degraded material that appears on the surface (chalking) and results in a reduction in gloss, color change and deterioration of mechanical properties.³

Manufacturers and Trade names: Eastman Thermx®, DuPont Engineering Polymers Zenite®, Ticona Vectran™ and Vectra®, Solvay Advanced Polymers Xydar®, Sumitomo Sumikasuper®, Toray Siveras®.

Applications and uses: Data for LCP plastics are found in Tables 5.1 and 5.2.

5.3 Polybutylene Terephthalate

PBT is semicrystalline, white or off-white polyester similar in both composition and properties to

PET. It has somewhat lower strength and stiffness than PET, and is a little softer but has higher impact strength and similar chemical resistance. As it crystallizes more rapidly than PET, it tends to be preferred for industrial scale molding. Its structure is shown in Fig. 5.5.

PBT performance properties include:

- High mechanical properties
- High thermal properties
- Good electrical properties
- Dimensional stability
- Excellent chemical resistance
- Flame retardancy

Weathering Properties: PBT products suffer from cracking, yellowing, loss of gloss and deterioration of tensile impact properties when exposed to UV light.⁵

Moldings made from Ultradur® and exposed to three years of open air weathering in central Europe tend to discolor very slightly and their surface scarcely changes. Mechanical properties such as rigidity, tensile strength and tear strength are slightly affected. After a weathering test for 3600 h in the Xenotest® 1200, the tensile strength retained is 90% of the initial value. However, elongation at break is more adversely affected. Based on experience, 3600 h in the Xenotest® 1200 equipment corresponds to about 5–6 years of weathering in open air. Parts for outdoor use should be manufactured from black-colored material in order to prevent

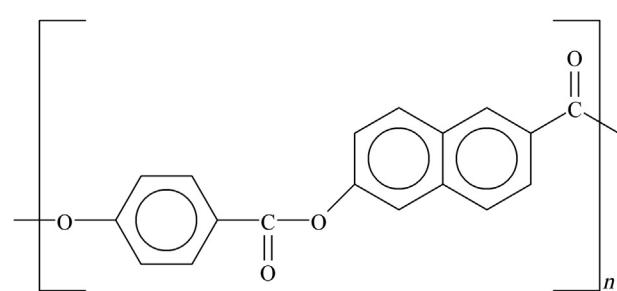
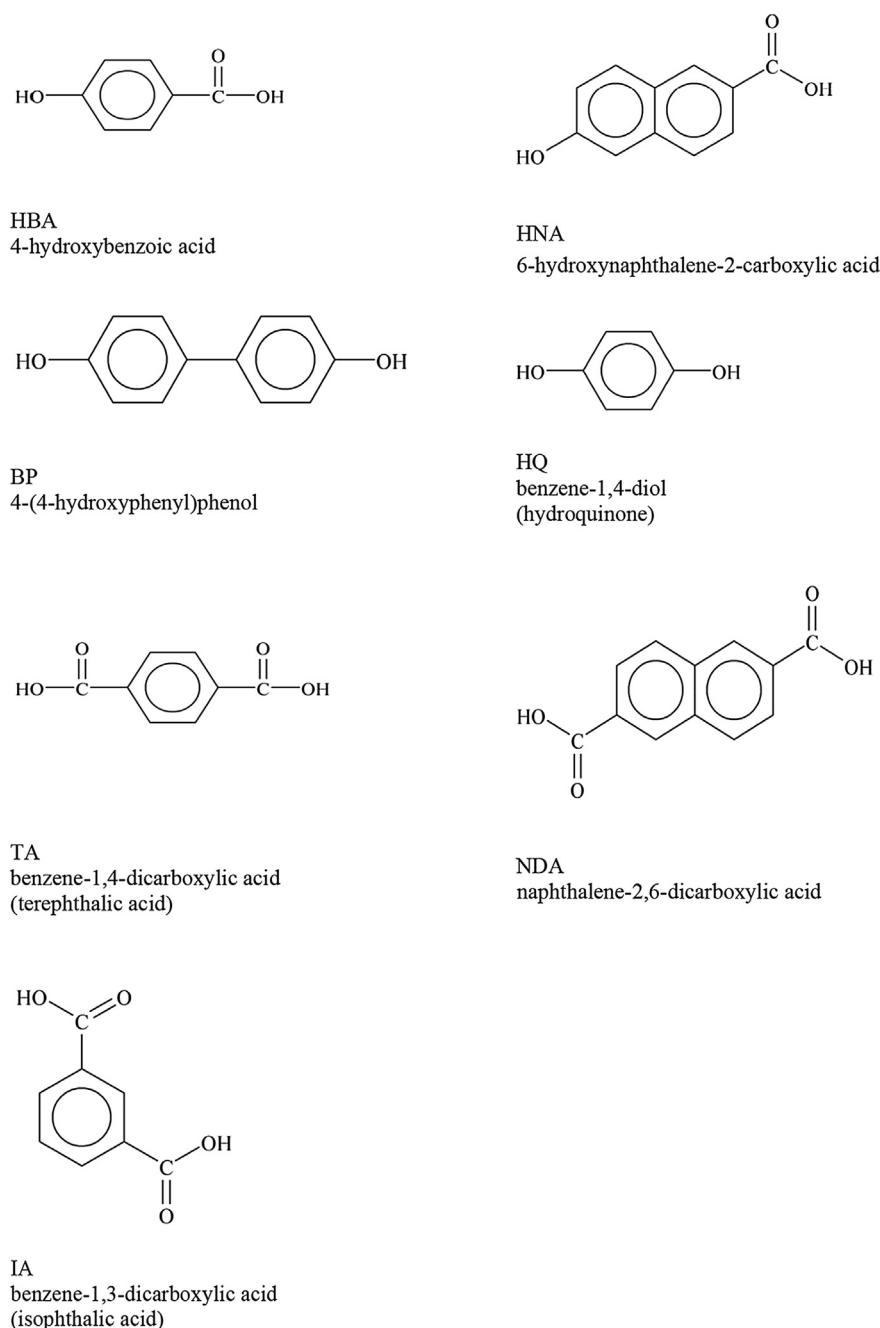


Figure 5.4 Chemical structure of Ticona Vectra[®] A950 LCP.

Figure 5.3 Chemical structures of monomers used to make liquid crystalline polymer polyesters.

impairment of strength due to surface attack. Fiber-reinforced PBT grades such as Ultradur[®] B 4040 G4/G6/G10 with outstanding surface quality and high resistance to UV radiation are suitable for parts that are subject to particularly extreme exposure. These grades have outstanding surface quality and exhibit high resistance to UV radiation.⁶

Results taken after three years of outdoor exposure indicate that there is no fundamental change in physical properties. Predictably, black Celanex[®]

Table 5.1 Results of Artificial Weathering for 2000 h of Ticona Vectra® A130 and Vectra® B950 LCPs⁴

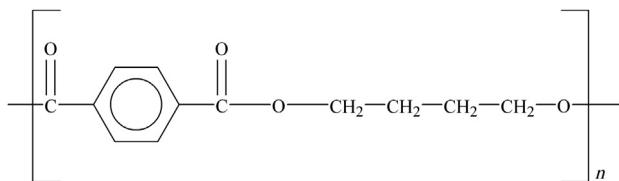
Properties Retained (%)	Vectra A950	Vectra A130	Test Method
Tensile Strength	95	95	ASTM D638
Tensile Modulus	90	98	ASTM D638
Flexural Strength	95	95	ASTM D790
Flexural Modulus	95	95	ASTM D790
HDT at 1.82 MPa	90	92	ASTM D648
Notched Izod	90	95	ASTM D256

Note: (1) ASTM D2565—xenon arc lamp, air temperature 125 °C, water spray for 18 min every 202 min.

Table 5.2 Mechanical Properties Retained after Xenon Arc Accelerated Weathering for Ticona Vectra® A950, Vectra® A130, Vectra® B950, and Vectra® A540 LCPs³

LCP Grade	Vectra® A950	Vectra® A130	Vectra® B950	Vectra® A540
Filler		30% Glass Fiber		40% Mineral
Properties Retained (%)				
Tensile Modulus	90	100	93	95
Flexural Modulus	100	100	95	100
Tensile Strength	97	97	100	100
Flexural Strength	100	100	100	100
Notched Izod Impact Strength	91	100	100	100
Heat Deflection Temperature	92	94	99	93

Note: (1) Test method: ASTM D2526, water spray for 18 min every 202 min. (2) Temperature 125 °C. (3) Exposure time: 83.3 days.

**Figure 5.5** Chemical structure of polybutylene terephthalate (PBT) polyester.

3300 polyester resin exhibits better property retention than natural resins and should therefore be considered where long-term outdoor exposure is required.⁷

Stabilization: Stabilizers for PBT are those discussed in the introduction of this chapter. However, Ciba Tinuvin® 234 and Tinuvin® 1577 can offer PBT products of high-quality UV protection.⁵

Manufacturers and trade names: BASF Ultradur®, DuPont Crastin®, PolyOne Burgadur™, SABIC Innovative Plastics Enduran, Ticona Celanex®.

Applications and uses: packaging, automotive, electrical and consumer markets.

Data for PBT plastics are found in Tables 5.3–5.6 and Figs 5.6–5.29.

These DuPont Engineering-Plastics Crastin® PBT products are presented in the following table and figures:

1. Crastin® S600F10 NC010 is an unreinforced, lubricated, medium high viscosity PBT resin for injection molding.
2. Crastin® SO655 NC010 is basic, 30% glass bead filled grade PBT resin.

Table 5.3 Ticona Celanex® PBT Polyesters—Color Difference and Gloss Change after 2 Years of Exposure in South Florida⁸

						60% Gloss Readings (%)		
Celanex® Grades	Condition	ΔL ^a	Δa ^a	Δb ^a	ΔE ^a	Initial	Final	Retention
1462Z BK225	As is	-3.62	0.20	0.87	3.73	24.0	5.0	20.8
	Washed	0.62	0.04	0.49	0.80	24.0	10.3	42.9
6500 BK225	As is	-5.05	0.25	0.61	5.09	88.0	14.4	16.4
	Washed	0.43	0.02	0.02	0.43	88.0	36.8	41.8
	Washed and polished	-3.26	0.01	-0.39	3.29	88.0	25.3	28.8
6407 ED3807	As is	-1.35	-0.15	0.12	1.36	44.5	3.2	7.2
	Washed	0.50	0.04	0.69	0.85	44.5	17.4	39.1
2002-2 ED3807	As is	-6.58	0.53	1.34	6.74	92.3	29.5	32.0
	Washed	-0.70	-0.01	0.39	0.80	92.3	67.7	73.3
	Washed and polished	-0.39	-0.09	-0.54	0.67	92.3	71.8	77.8

Note: (1) Test method: SAE J1976.

^aΔ means the change in the value (*i.e.* the exposed value minus the initial value).

Table 5.4 Changes in Color and Gloss of Ticona Celanex® PBT Polyester Prototype Parts after 2500 kJ/m² Exposure to Xenon Arc⁸

Celanex® Grades	Part Description	Surface	Condition	ΔL*	Δa*	Δb*	ΔE*
6500 BK225	F-car wiper airfoil	Textured	As is	-1.96	0.27	1.61	2.55
			Washed	1.70	-0.01	0.27	1.72
			Washed and polished	0.16	0.02	0.32	0.36
2002-2 ED3807	F-car wiper cover	Textured	As is	0.87	-0.73	2.50	2.82
			Washed	3.77	-0.06	0.16	3.77
6407 ED3807	Luggage rack rail	Smooth	As is	0.15	0.19	0.77	0.81
			Washed	-0.81	-0.49	-0.01	0.94

Note: (1) Test method: SAE J1960.

Table 5.5 Mechanical Property Retention of Ticona Celanex® PBT Polyesters after 2500 kJ/m² Exposure to Xenon Arc⁸

Properties Retained (%)	Units	Celanex® 6500 BK225	Celanex® 6407 ED3807
Tensile Strength at Break	%	97	97
Elongation at Break	%	94	93
Notched Izod	%	102	89
Flexural Strength	%	94	92
Flexural Modulus	%	101	100

Note: (1) Test method: SAE J1960.

Table 5.6 Retention of Properties after Natural Weathering in Central Germany for Three DuPont Crastin® PBT Grades⁹

Crastin® Grade Test Method	Weathering Time (Years)	Tensile Strength (%) DIN 53455	Tensile Modulus (%) DIN 53457	Flexural Strength (%) DIN 53452	Charpy Impact Strength Unnotched (%) ISO 179	Charpy Impact Strength Unnotched (%) ISO 179
S600F10 NC010	0	100	100	100	NB	100
	1/2	92	102	99	NB	33
	1	96	107	101	NB	40
	2	91	108	99	NB	41
	3	91	89	101	92.9 kJ/m ²	45
	4	93	98	98	89.5 kJ/m ²	29
SK605 NC010	0	100	100	100	100	100
	1/2	87	93	96	90	100
	1	92	87	91	82	99
	2	75	95	79	64	89
	3	81	97	81	68	83
	4	76	83	79	52	81
SO655 NC010	0	100	100	100	100 (100) ^a	100
	1/2	92	86	9/8	47 (61)	60
	1	90	92	100	65 (69)	58
	2	83	98	93	61 (72)	60
	3	85	83	91	55 (60)	57
	4	85	90	87	43 (68)	52

Note: (1) Change of properties vs. unexposed products.

^aIn this case the values are based on the value at the beginning of the storage. The figures in parenthesis represent the impact strength change of nonexposed samples and depend on the storage time in the test laboratory vs. the initial start of the test program.

3. Crastin® SK605 BK851 is 50% glass fiber reinforced, lubricated, black PBT resin for injection molding.
4. Crastin® SK603 NC010 is 20% glass fiber reinforced, lubricated PBT resin for injection molding.
5. Crastin® SK605 NC010 is 30% glass fiber reinforced, lubricated PBT resin for injection molding.
6. Crastin® SK645FR NC010 is a flame retardant, 30% glass reinforced natural PBT molding resin. It is recognized as UL94V-0 at 0.75 mm.
7. Crastin® SK602 NC010 is 15% glass fiber reinforced, lubricated PBT resin for injection molding.
8. Crastin® HTI619 NC010 is a 50% glass/mineral reinforced, high-tracking PBT resin.
9. Crastin® HTI681 NC010 is a low-warpage glass bead/mineral-reinforced, high-tracking PBT resin.
10. Crastin® T805 NC010 is a 30% glass fiber reinforced, high-impact PBT resin for injection molding.
11. Crastin® LW9130 NC010 is a low-warpage, 30% glass-reinforced PBT resin.

5.4 Polycarbonate

Theoretically, PC is formed from the reaction of bis-phenol A and carbonic acid. The structures of these two monomers are given in Fig. 5.30.

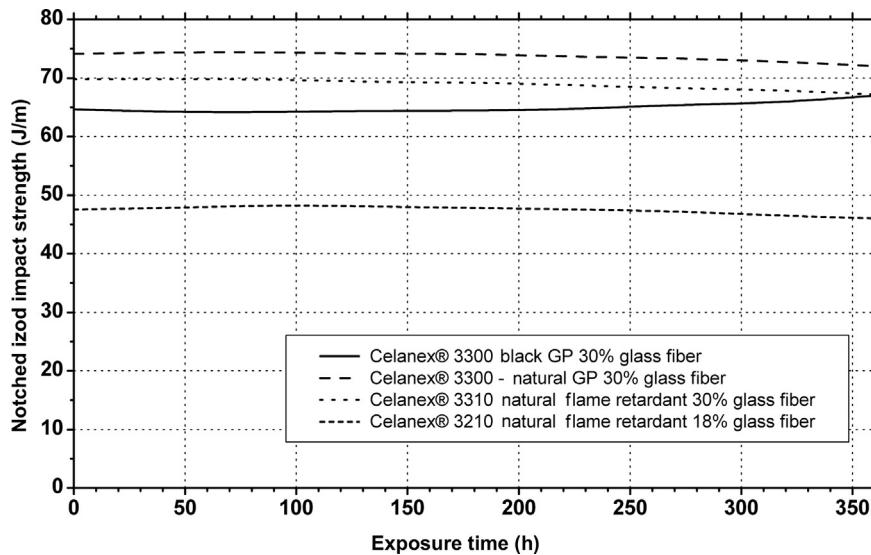


Figure 5.6 Notched Izod impact strength after Florida and Arizona outdoor weathering for Ticona Celanex® PBT.¹⁰

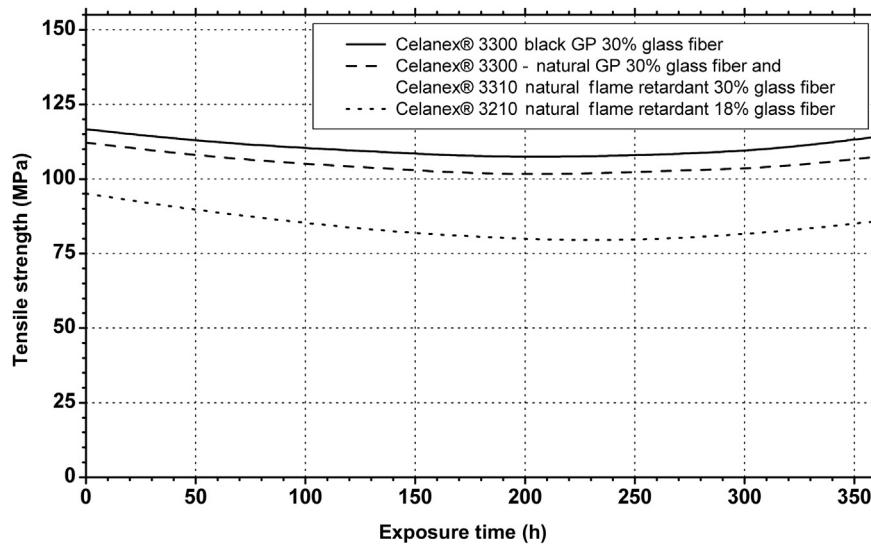


Figure 5.7 Tensile strength after Florida and Arizona outdoor weathering for Ticona Celanex® PBT.¹⁰

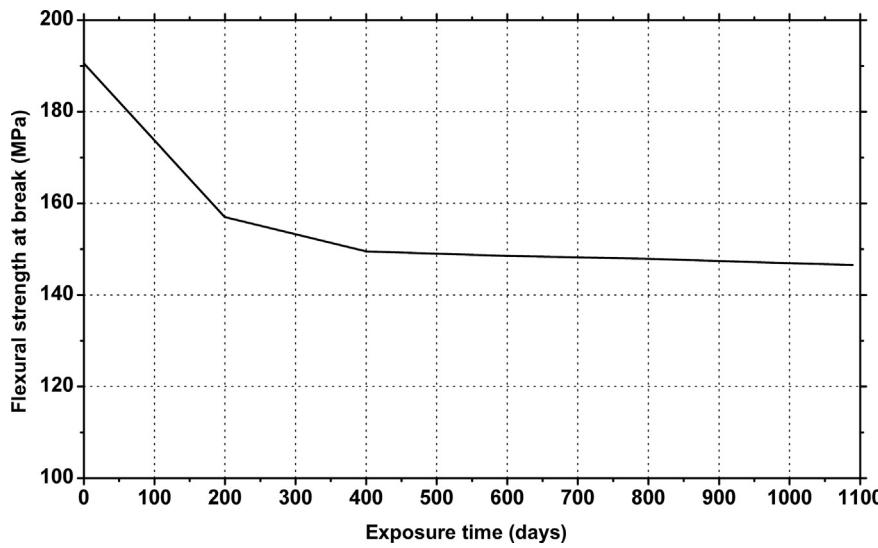


Figure 5.8 Flexural strength at break after Hiratsuka, Japan, outdoor exposure of PBT polyester.¹¹

Figure 5.9 Flexural modulus after Hiratsuka, Japan, outdoor exposure of PBT polyester.¹¹

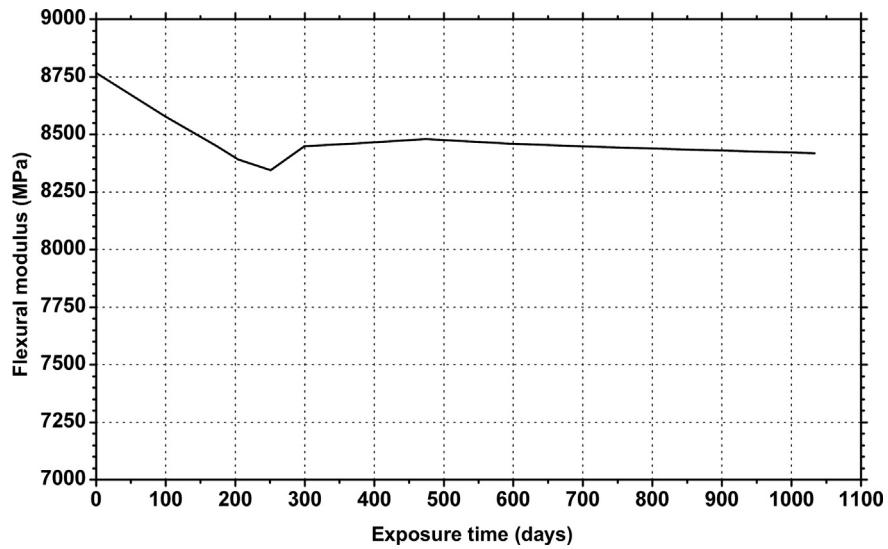


Figure 5.10 Notched Izod impact strength after Hiratsuka, Japan, outdoor exposure of PBT polyester.¹¹

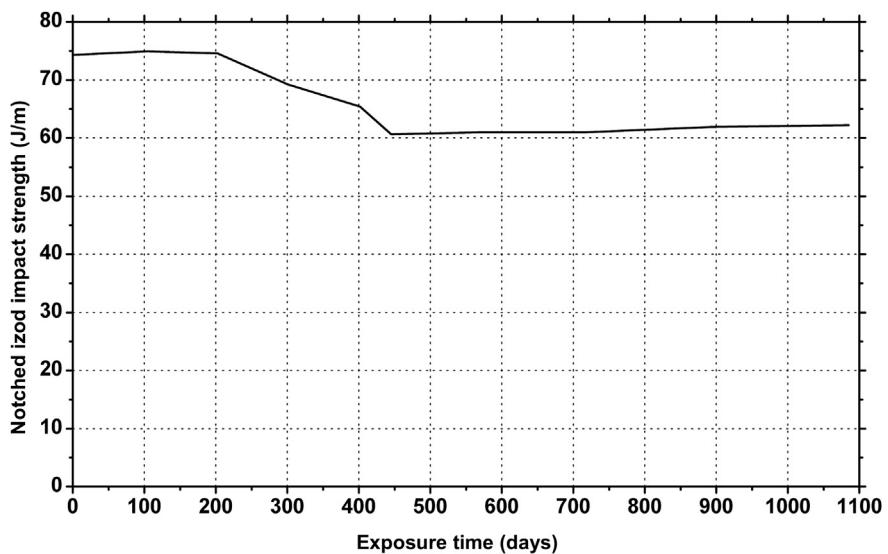
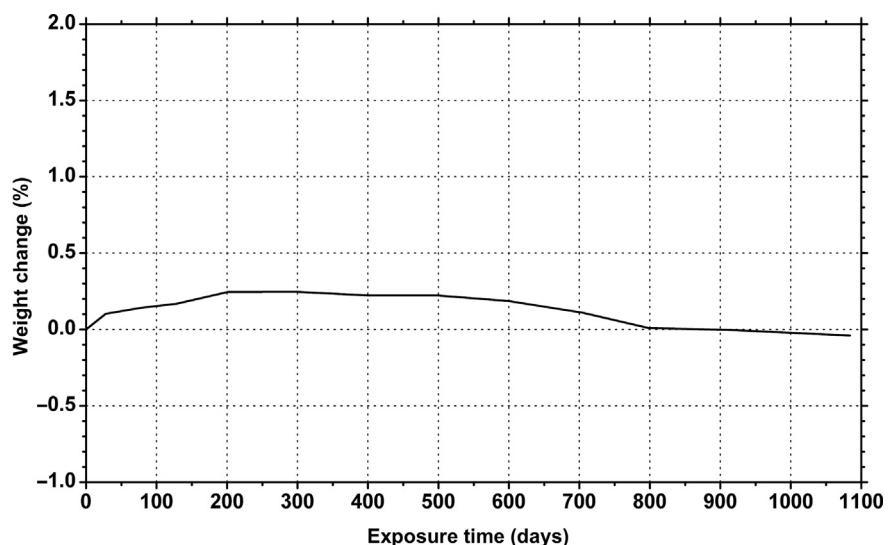


Figure 5.11 Weight change after Hiratsuka, Japan, outdoor exposure of PBT polyester.¹¹



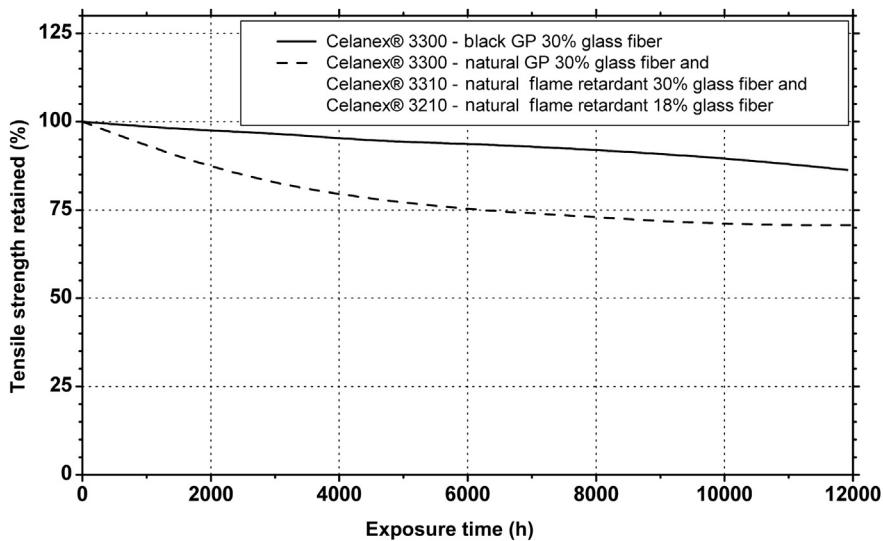


Figure 5.12 Tensile strength retained after Weather-Ometer® exposure of Ticona Celanex® PBT.¹⁰

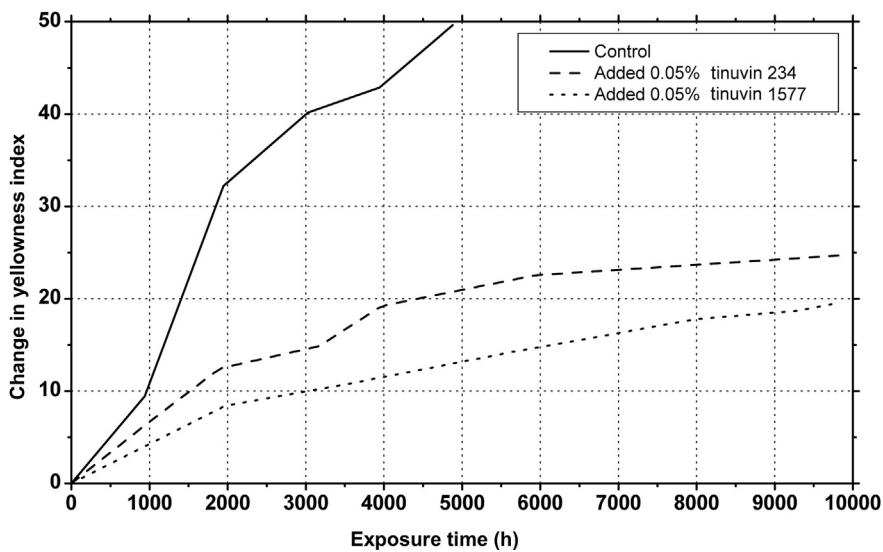


Figure 5.13 Change in yellowness index, YI, after light exposure of PBT injection-molded plaques.⁵
Note: Xenon arc weathering, ISO 4892-2, cycle 102/18; 1 mm plaques; base stabilization: 0.10% Irganox® 1010 and 0.40% Irgafos® 168 (Irganox® B 561).

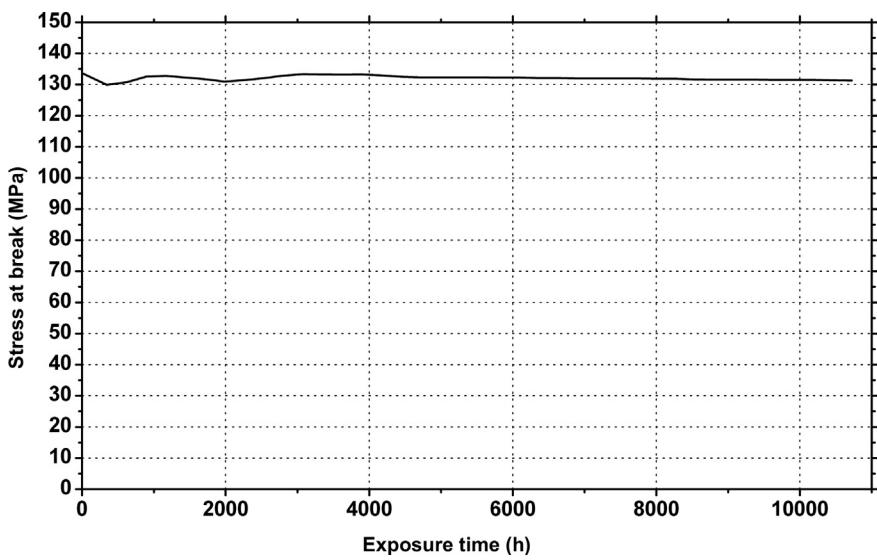


Figure 5.14 Stress at break of BASF Ultradur® PBT after weathering with xenon arc per ISO 4892-2 ref. A.¹²

Figure 5.15 Stress at break of BASF Ultradur® high speed PBT after weathering per xenon arc ISO 4892-2 ref. A.¹²

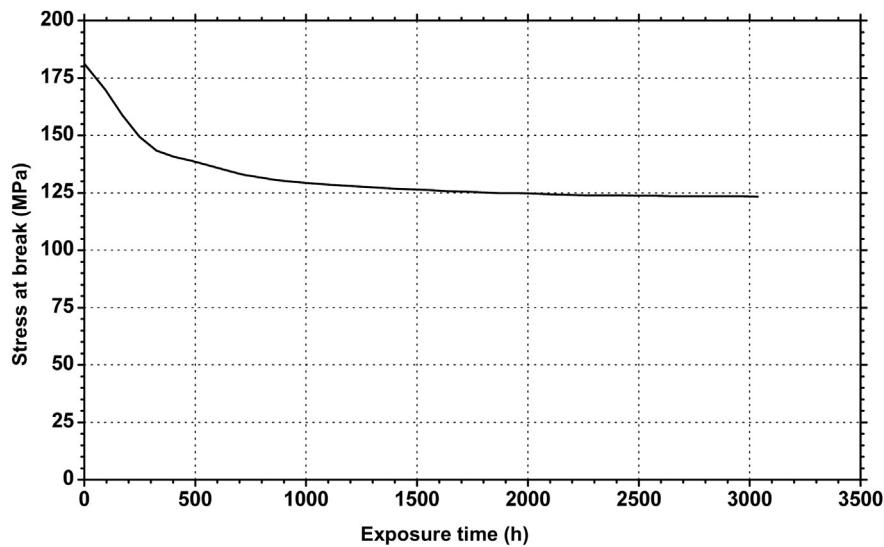


Figure 5.16 Charpy impact strength of Ultradur® PBT after different weathering with xenon arc per ISO 4892-2 ref. A.¹²

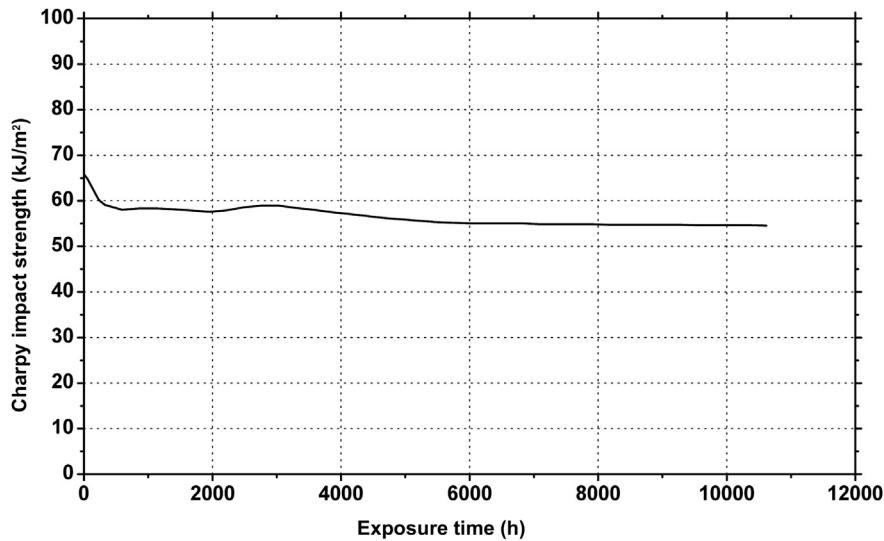
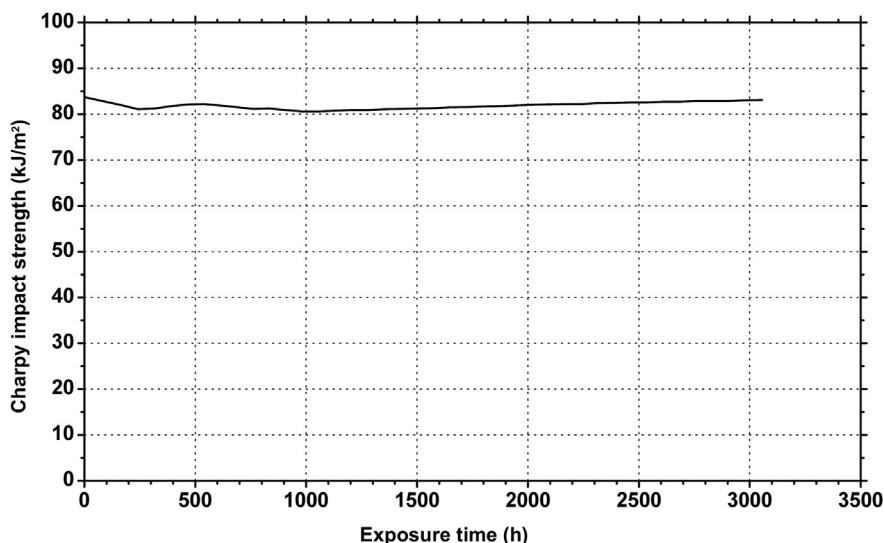


Figure 5.17 Charpy impact strength of Ultradur® high speed PBT after weathering with xenon arc per ISO 4892-2 ref. A.¹²



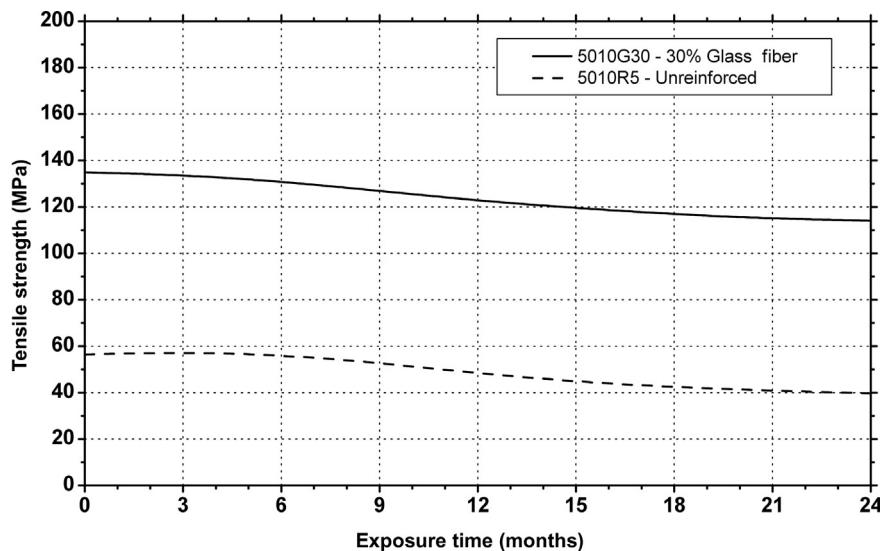


Figure 5.18 Tensile strength vs. outdoor exposure at Kitakyusyu city Japan of Mitsubishi Engineering-Plastics Novaduran PBT.¹³

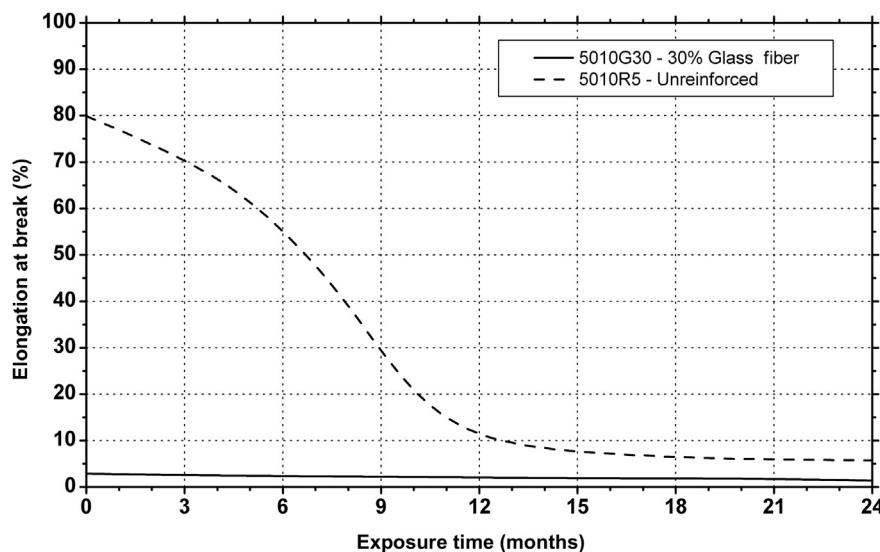


Figure 5.19 Elongation at break vs. outdoor exposure at Kitakyusyu city Japan of Mitsubishi Engineering-Plastics Novaduran PBT.¹³

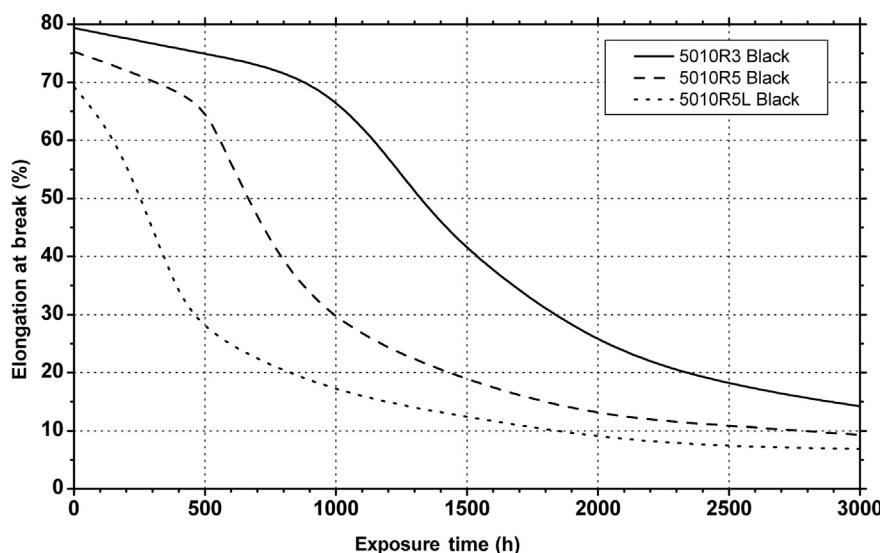


Figure 5.20 Elongation at break vs. sunshine carbon arc exposure at 63 °C with rain 12/60 min of Mitsubishi Engineering-Plastics Novaduran Black PBT.¹³

Figure 5.21 Tensile strength vs. sunshine carbon arc exposure at 63 °C with rain 12/60 min of Mitsubishi Engineering-Plastics Novaduran PBT.¹³

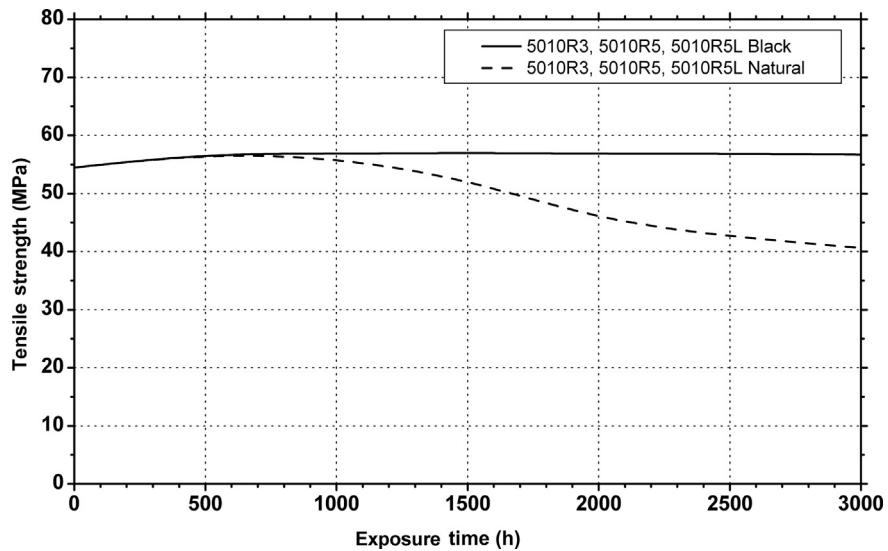


Figure 5.22 Tensile strength vs. sunshine carbon arc exposure at 63 °C with no rain of Mitsubishi Engineering-Plastics Novaduran PBT.¹³

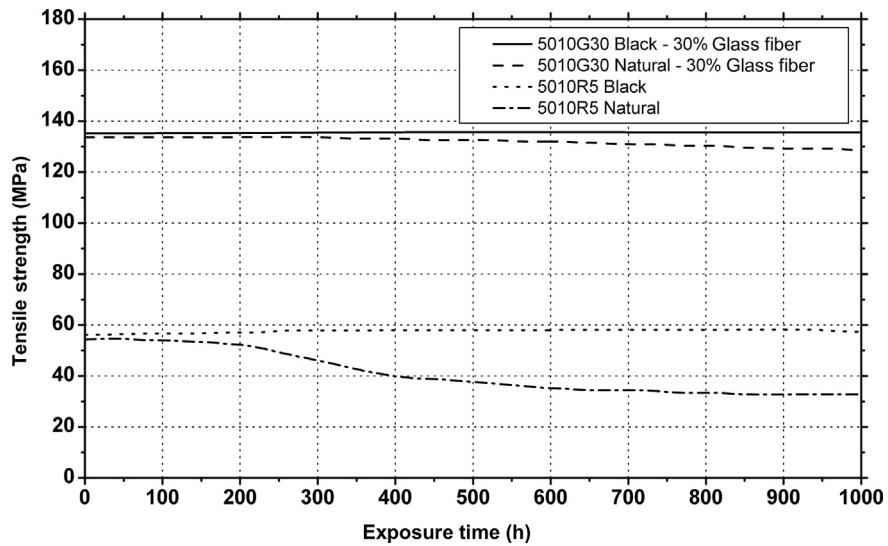
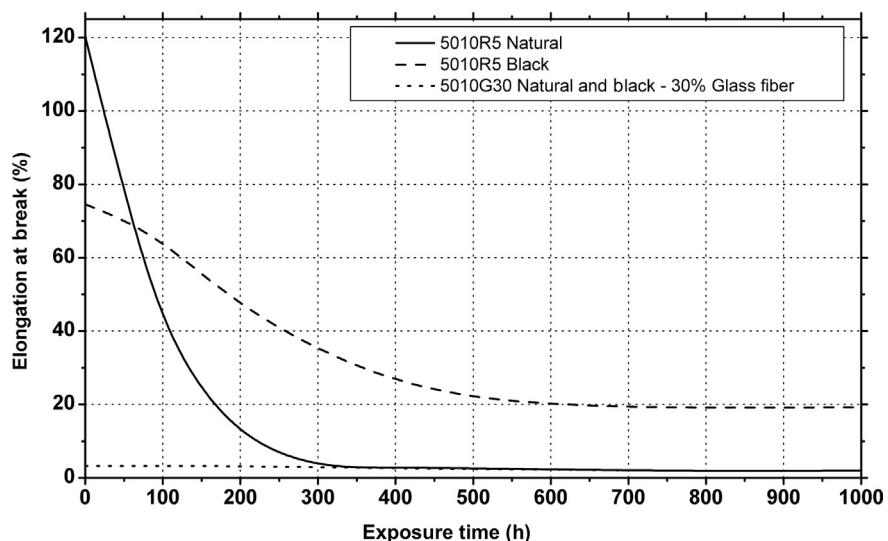


Figure 5.23 Tensile fracture strain vs. sunshine carbon arc exposure at 63 °C with no rain of Mitsubishi Engineering-Plastics Novaduran PBT.¹³



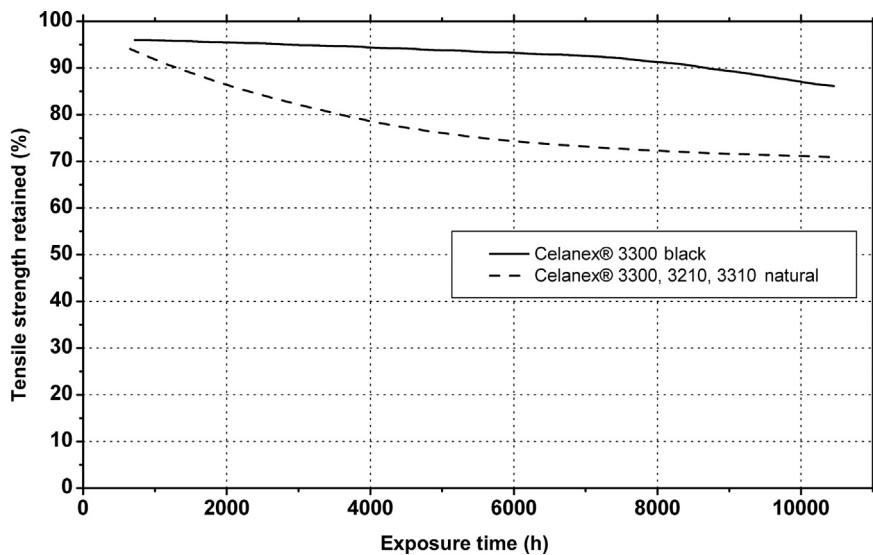


Figure 5.24 Weather-Ometer® exposure effects on tensile strength, glass reinforced grades of Ticona Celanex® PBT polyester.⁸

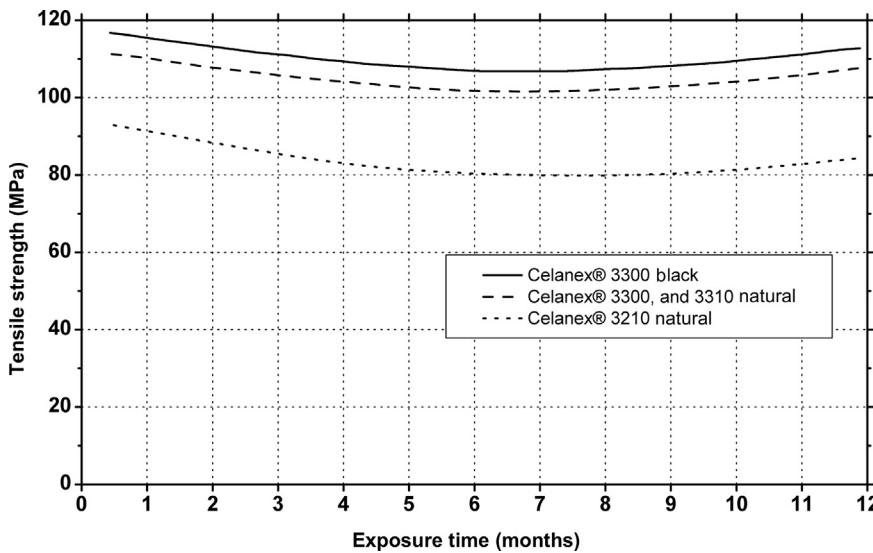


Figure 5.25 Tensile strength vs. outdoor exposure in Florida and Arizona, glass reinforced grades of Ticona Celanex® PBT polyester.⁸

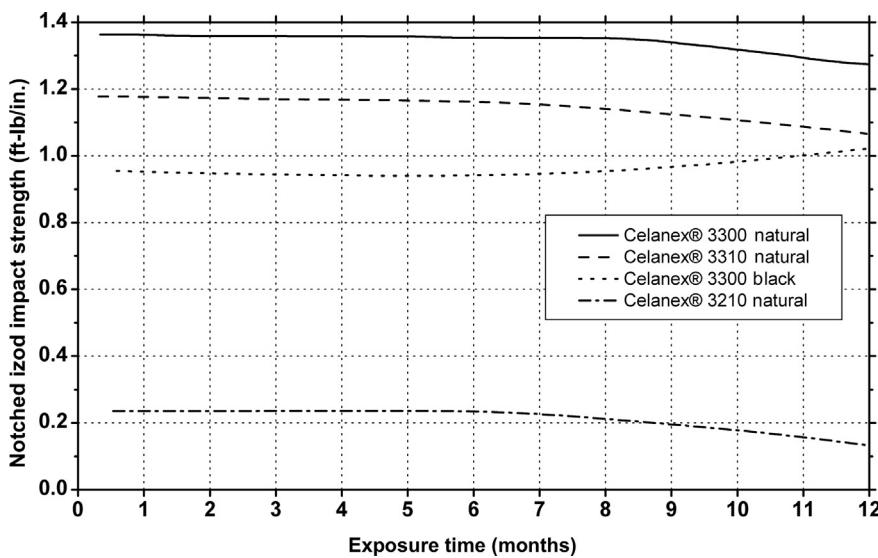


Figure 5.26 Izod impact vs. outdoor exposure in Florida and Arizona, glass reinforced grades of Ticona Celanex® PBT polyester.⁸

Figure 5.27 Effect of weathering on flexural strength of some DuPont Crastin® PBT grades.⁹

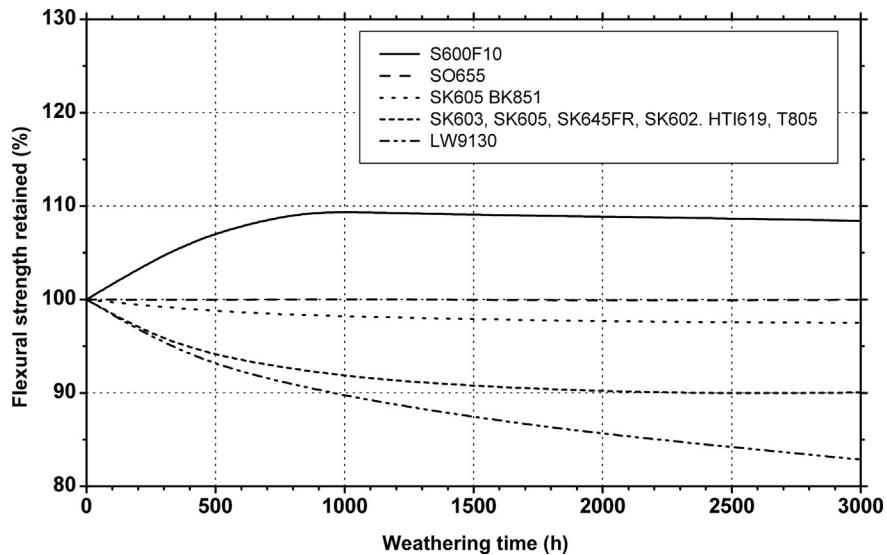


Figure 5.28 Impact resistance (DIN53452) vs. weathering time of some DuPont Crastin® PBT grades.⁹

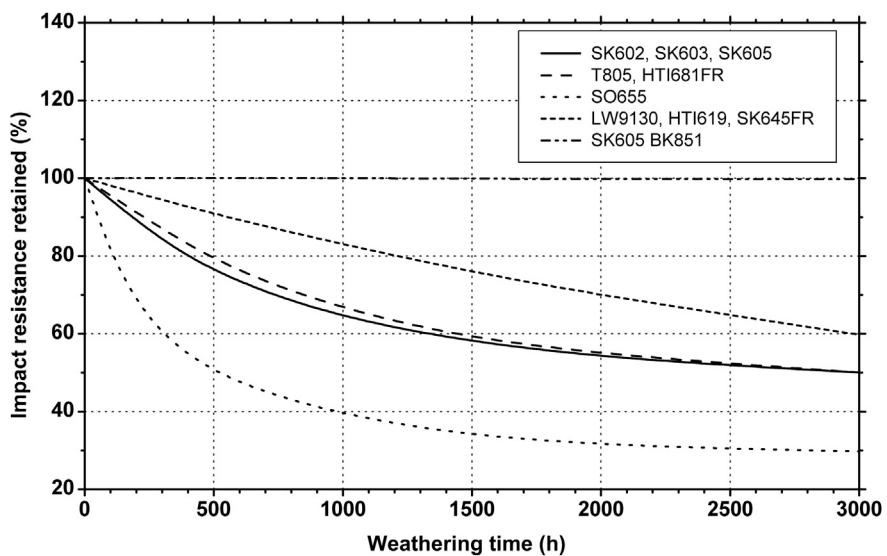
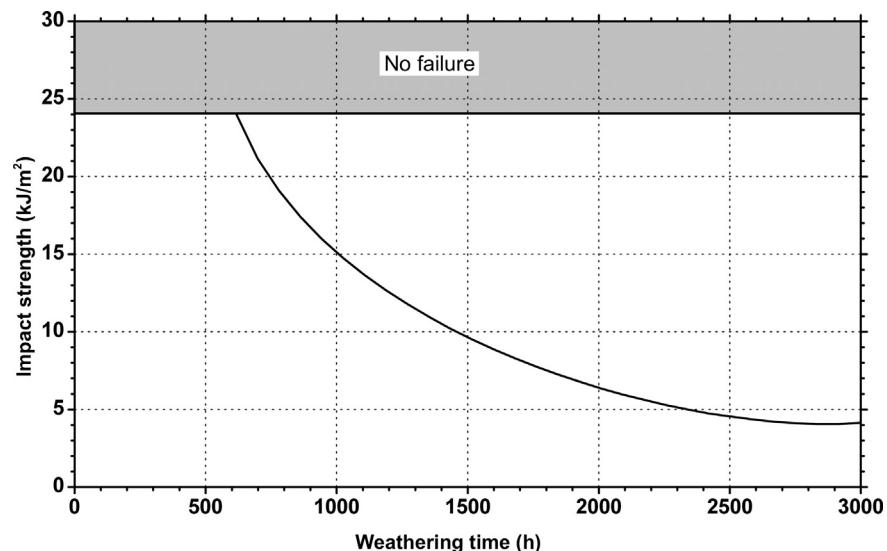


Figure 5.29 Impact strength vs. weathering time of DuPont Crastin® S600F10 NC010.⁹



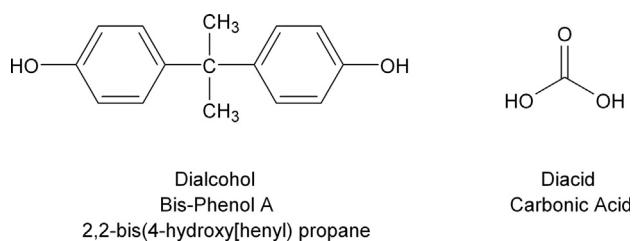


Figure 5.30 Chemical structures of monomers used to make polycarbonate polyester.

Commercially, different routes are used (different monomers), but the PC polymer of the structure shown in Fig. 5.31 is the result.

PC performance properties include:

- Very high impact resistance and is virtually unbreakable and remains tough at low temperatures
- “Clear as glass” clarity

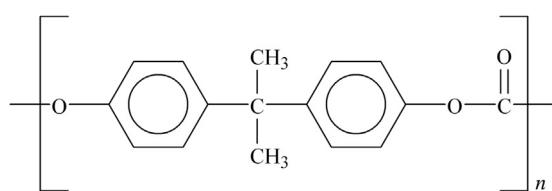


Figure 5.31 Chemical structure of polycarbonate (PC) polyester.

- High heat resistance
- Dimensional stability
- Resistant to ultraviolet light, allowing exterior use
- Flame retardant properties

Weathering Properties: PC is used in building applications, mainly as glazing material. “When irradiated with short wavelength UV-B or UV-C radiation, PCs undergo reactions referred to as

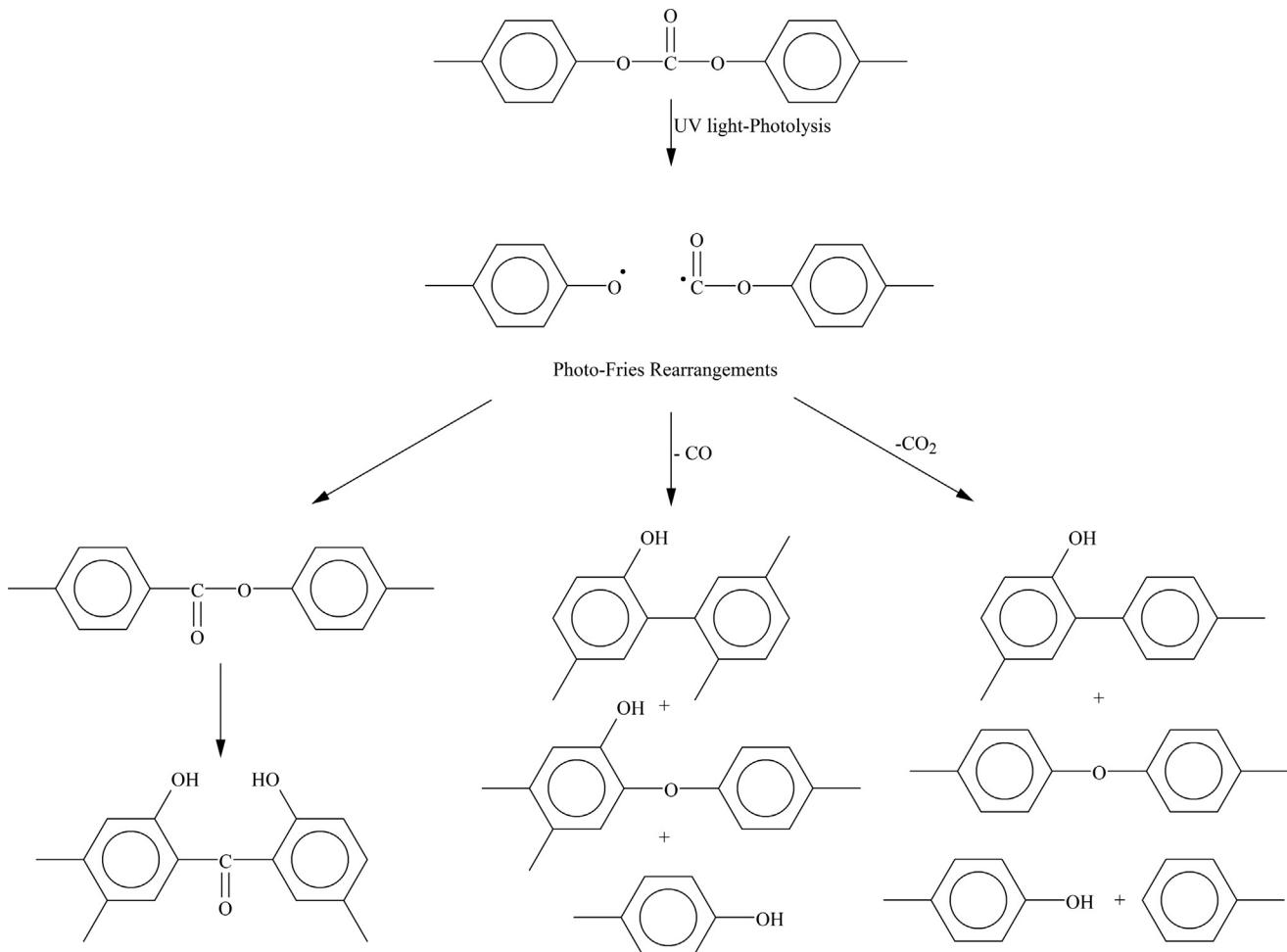


Figure 5.32 The photo-Fries rearrangement in polycarbonate.

Table 5.7 Izod Impact and Surface and Appearance Properties after Arizona Outdoor Exposure of Dow Calibre® 300 6 MFR with and without UV Stabilizer¹⁵

Features	Without UV Stabilizer				With UV Stabilizer			
	0	6 Months	1 Year	2 Years	0	6 Months	1 Year	2 Years
Mechanical Properties								
Izod Impact (ft-lb/in.)	17.6	17.9	1.2	0.6	18.2	17.9	17.7	18.5
Surface and Appearance								
Transmittance (%)	89.4	85.8	84.7	82.3	89.6	88.4	88.5	87.3
Haze (%)	1.7	8.2	12.7	19.8	1.6	6.8	9.0	14.8
Yellowness Index Increase	0	+12.3	+15.7	+20.0	0	+2.3	+3.3	+6.1

Note: (1) Exposure conditions Arizona, 45° angle facing south. (2) Exposure time 2 years.

Table 5.8 Mechanical Properties Retained after California and Pennsylvania Outdoor Exposure of LNP Engineering Plastics PC¹⁶

Exposure Location	Los Angeles, CA				Philadelphia, PA			
Exposure Time (Days)	91	182	365	730	91	182	365	730
Properties Retained (%)								
Tensile Strength	90	90.4	89	87	88	86	89	87
Notched Izod Impact Strength	94	83.3			94	83.3		
Unnotched Izod Impact Strength	83	72.3			80	73.8		

Note: (1) ASTM 1435. (2) Composition: 1% carbon black, 30% glass fiber.

Table 5.9 Mechanical Properties and Surface and Appearance Properties after Arizona Accelerated Outdoor Weathering and Kentucky Outdoor Weathering for GE Lexan® S-100 and Lexan® 100 PC Sheet¹⁷

Material Characteristics						
Sample Thickness (mm)	3.28	2.36	3.28	2.36	3.28	2.36
Exposure Conditions						
Exposure Location	Arizona		Florence, Kentucky		Arizona	
Exposure Apparatus	EMMAqua				Carbon arc Weather-Ometer®	
Exposure Note			45° angle south			
Exposure Time (Days)	365	365	730	730	125	125
Properties Retained (%)						
Tensile Strength					101	98
Notched Izod Impact Strength					84.2	64.7
Charpy Notched Impact Strength					10.9	55.7
Surface and Appearance						
ΔYellowness Index	17.29	20.91	10.46	9.0	25.43	25.0
Luminous Transmittance Retained (%)					90.6	88.4

Table 5.10 Mechanical Properties Retained after X-W Accelerated Weathering for GE Lexan® 303 PC¹⁸

Exposure Time (Days)	41.7	83.3	166.7	333.3
Properties Retained (%)				
Notched Izod Impact Strength	42	9	9	9
Tensile Impact Strength	30	38	29	
Heat Deflection Temperature	100.8	101.5	100	98.5

Table 5.11 Influence of Pigment Addition to in Mitsubishi Engineering-Plastics Iupilon®/Novarex PC in Outdoor Exposure test¹⁹

Type of Pigment Additive Amount (%)	Additive Amount (%)	pH	Untreated	Outdoor Exposure 1 Year		Thickness (μm)
			Molecular Weight (×10 ⁴)	Molecular Weight (×10 ⁴)	ΔE	
Blue Pigment	0.2	9.4	2.8	2.1	5.6	50
Red Oxide	0.2	7.6	2.8	2.1	4.9	50
Shanin Green	0.2	6.5	2.8	2.1	4.3	50
Cadmium Yellow M3600	0.2	7.3	2.8	2.1	2.2	50
Cadmium Yellow M3200	0.2	7.2	2.8	2.1	1.8	50
Cadmium Red L6600	0.2	8.2	2.8	2.2	2.6	50
Cadmium Red M8300	0.2	8.2	2.8	2.1	2.7	50
Cadmium Red 05700	0.2	8.1	2.8	2.6	2.9	50
0.2 Shanin Blue LBGT	8.0	2.8	2.3	1.0	50	
Carbon Blacks						
Nippiru#100 (Nittetsu)	0.5	4.7	2.8	2.4	3.0	50
FB44 (Mitsubishi Carbon)	0.5	7.7	2.8	2.3	3.8	50
#50 (Mitsubishi Carbon)	0.5	6.0	2.8	2.3	4.5	50
#600 (Mitsubishi Carbon)	0.5	7.0	2.8	2.5	5.6	50
For Rubber H (Mitsubishi Carbon)	0.5	7.7	2.8	2.5	2.5	50
Mark (Columbia)	0.5	3.0	2.8	2.4	9.0	50
#999 (Columbia)	0.5	2.8	2.3	7.0	50	
Blank	0		3.9	2.8	1.8	8.2
Titanium White R820	0.7		2.8		13.6	200
Titanium White R101	0.7		2.8		14.4	200
Carbon Black (For Rubber H)	0.5		2.8		2.0	200
Carbon Black (#100)	0.5		2.8	2.6	4.4	200
Blank	0		2.8	2.0	11.0	200

Table 5.12 Influence of UV Stabilizer and Titanium Dioxide (TiO_2) Content in Mitsubishi Engineering-Plastics Iupilon[®]/Novarex PC in Exposure Test Performance Test¹⁹

	Additives (%)		Change in Melt Viscosity by Exposure test ($\times 10^4$)					Generation Rate of Brittle Break by Falling Ball Test (%)				
	UV	TiO_2	0 Year	2 Years	3 Years	4 Years	5 Years	0 Year	1 Year	2 Years	3 Years	4 years
1	0	0	3.1	2.8	2.7	2.6	2.5	0	90	100	100	100
2	0.4	0	3.1	3.0	3.0	3.0	3.0	0	0	0	0	0
3	0	0.5	3.1	2.8	2.6	2.6	2.6	0	5	15	100	100
4	0.4	0.5	3.0	2.7	2.6	2.6	2.6	0	0	0	0	25

Note: (1) Sample thickness 2.5 mm, (2) The falling ball test drops the steel ball of 3.6 kg from the height of 3.85 m on a hemisphere body of 146 mm inside diameter and examines the breaking situation.

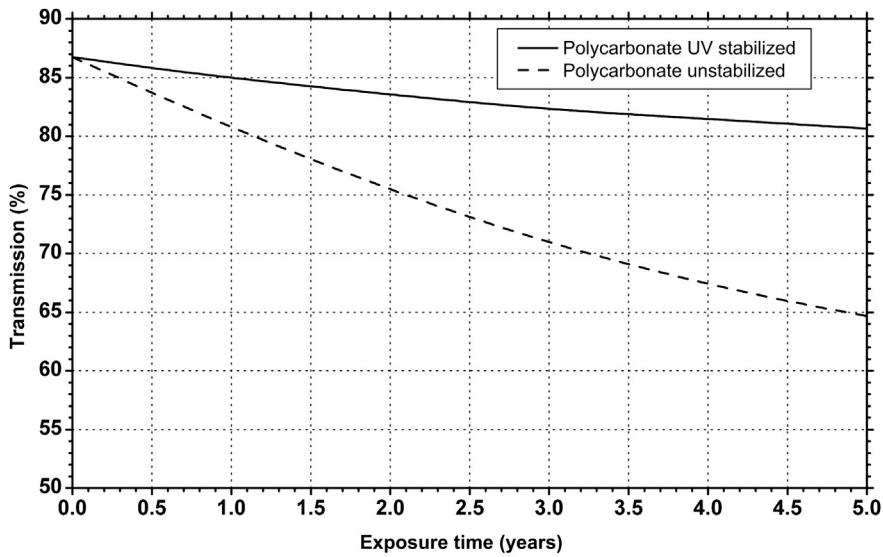


Figure 5.33 Transmittance through transparent GE plastics Lexan® PC after Florida outdoor exposure as per ASTM G7.²⁰

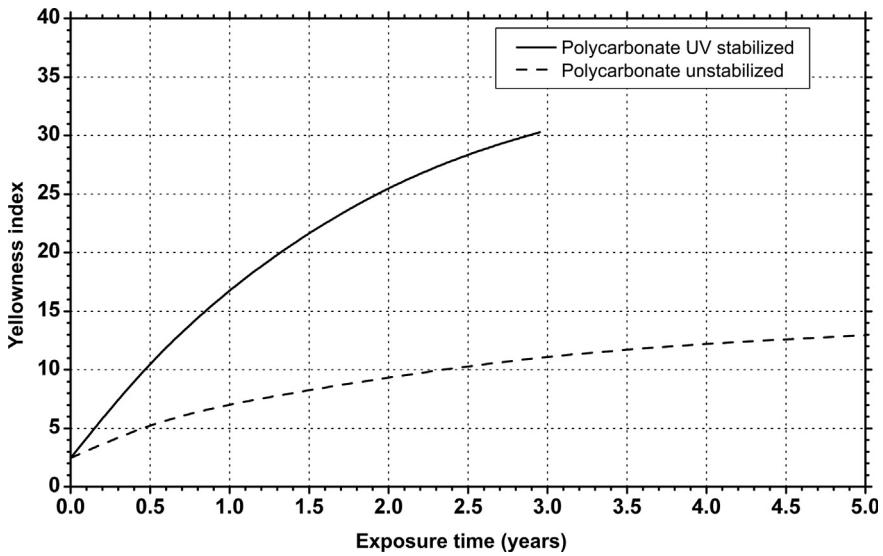


Figure 5.34 Yellowness index after Florida outdoor exposure as per ASTM G7 for GE plastics Lexan® PC.²⁰

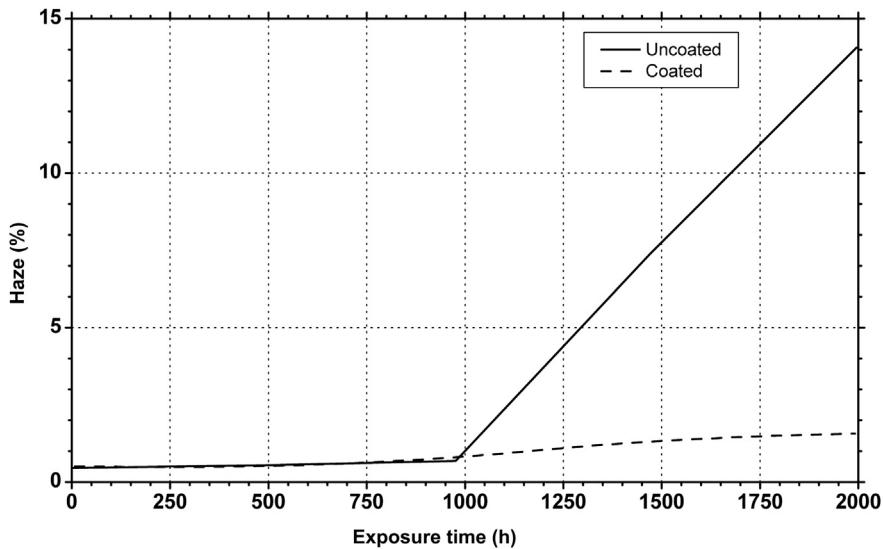


Figure 5.35 Haze after accelerated outdoor exposure of coated and uncoated transparent GE plastics Lexan® PC.²⁰

Figure 5.36 Yellowness index after accelerated outdoor exposure of coated and uncoated transparent GE plastics Lexan® PC.²⁰

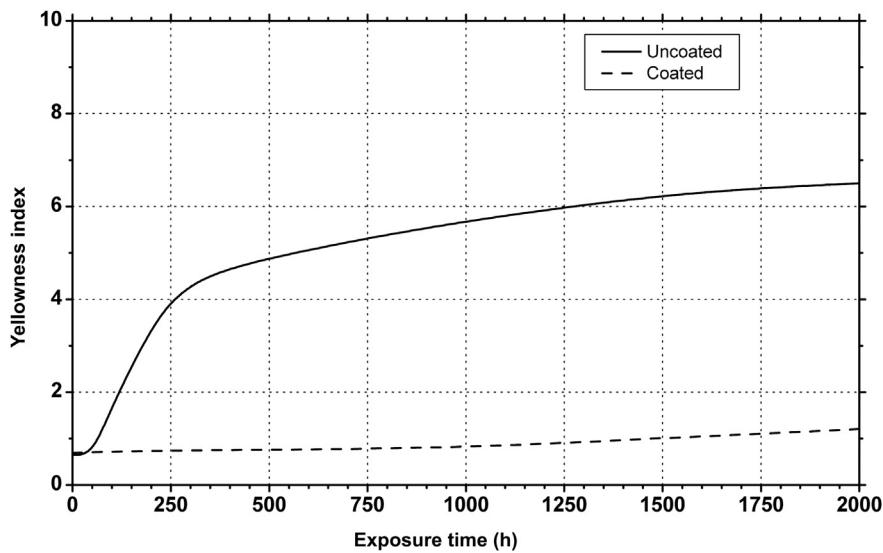


Figure 5.37 Yellowness index after xenon arc weathering for GE plastics Lexan® PC.²⁰

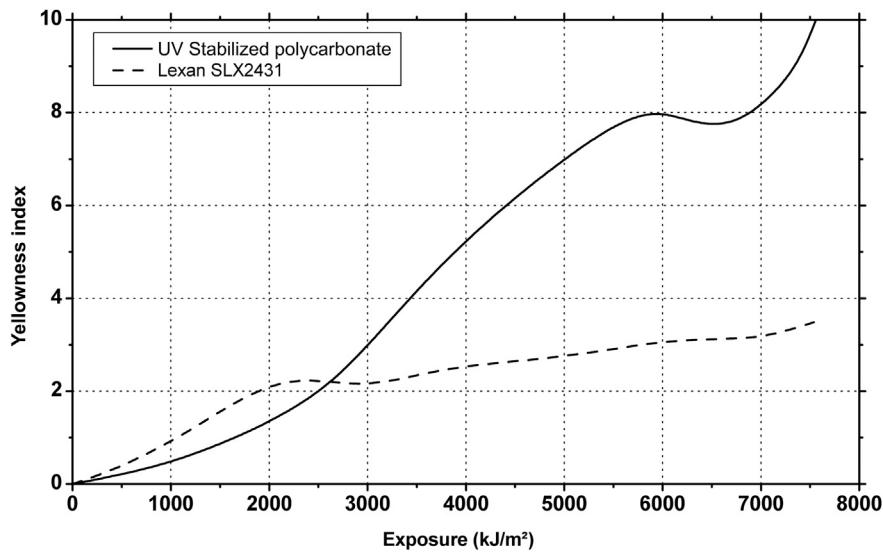
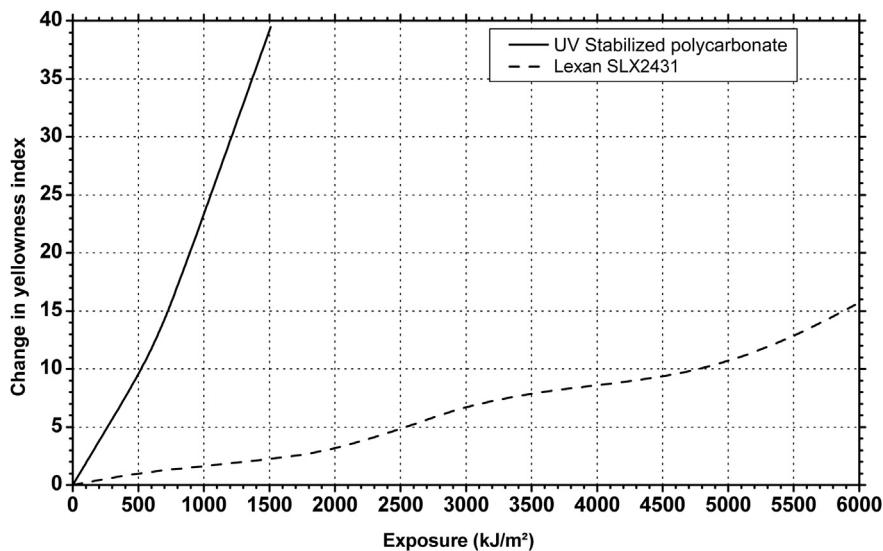


Figure 5.38 Change in yellowness index, YI, after whirlygig accelerated outdoor exposure of GE plastics Lexan® PC.²⁰



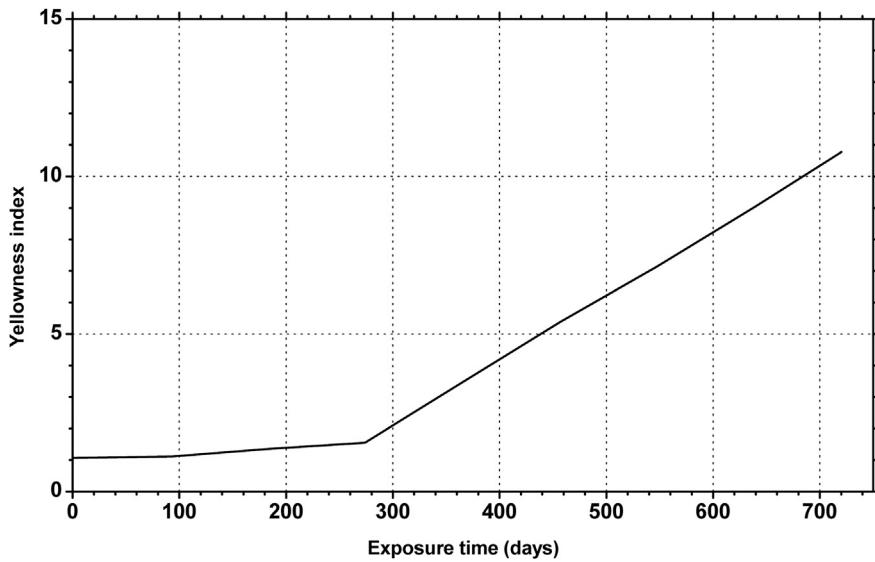


Figure 5.39 Yellowness index after Kentucky outdoor weathering for GE Lexan® S-100 sheet PC.¹⁷

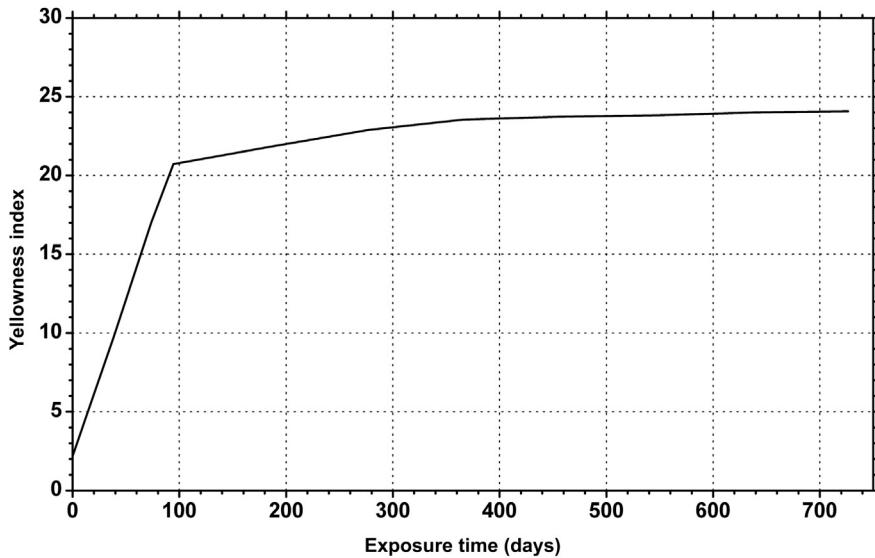


Figure 5.40 Yellowness index after EMMAqua® accelerated arizona weathering for GE Lexan® S-100 sheet PC.¹⁷

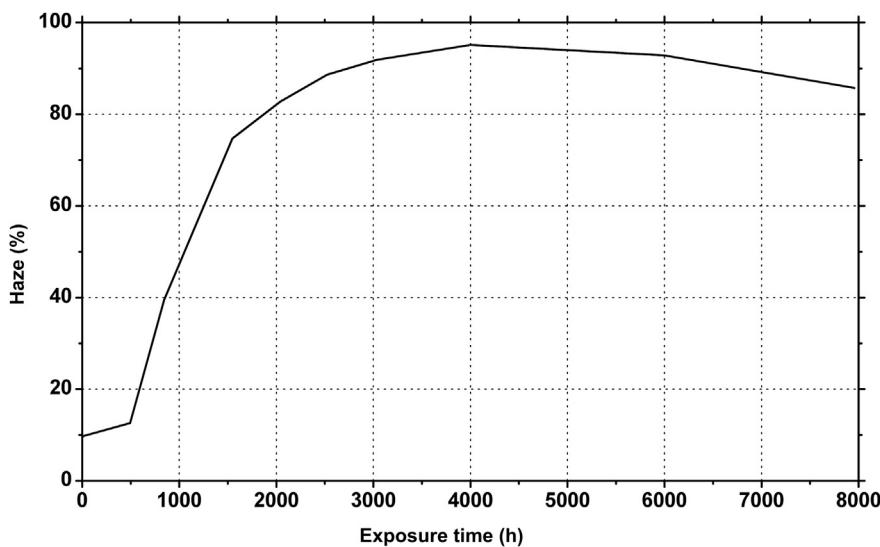


Figure 5.41 Haze (%) after carbon arc X-W weathering for GE Lexan® 153 PC.¹⁸

Figure 5.42 Yellowness index after twin carbon arc weathering for GE Lexan® S-100 PC sheet.¹⁷

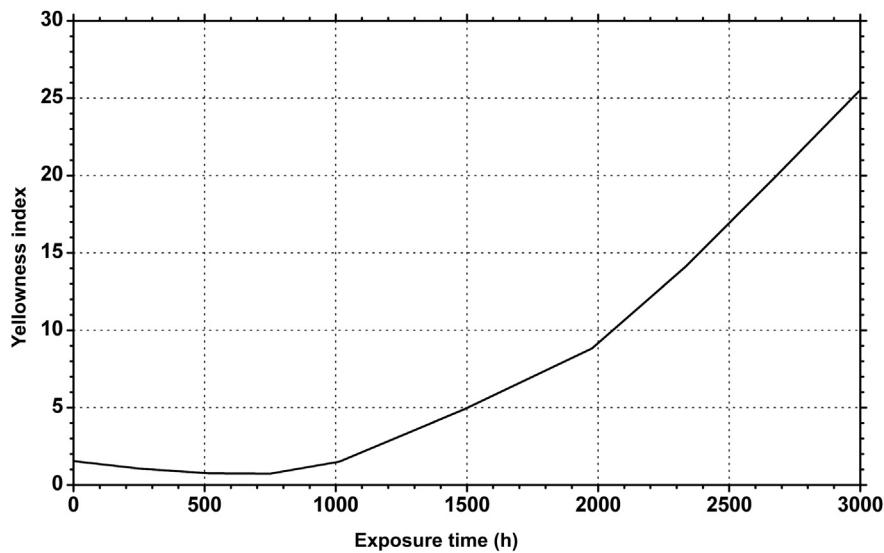


Figure 5.43 Change in discoloring to yellow of Mitsubishi Engineering-Plastics lupilon/Novarex PC by outdoor exposure.¹⁹

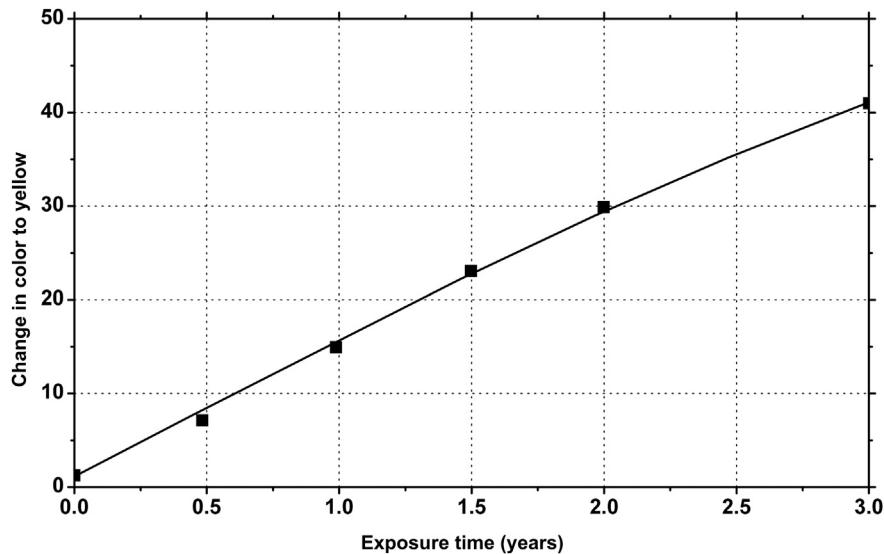
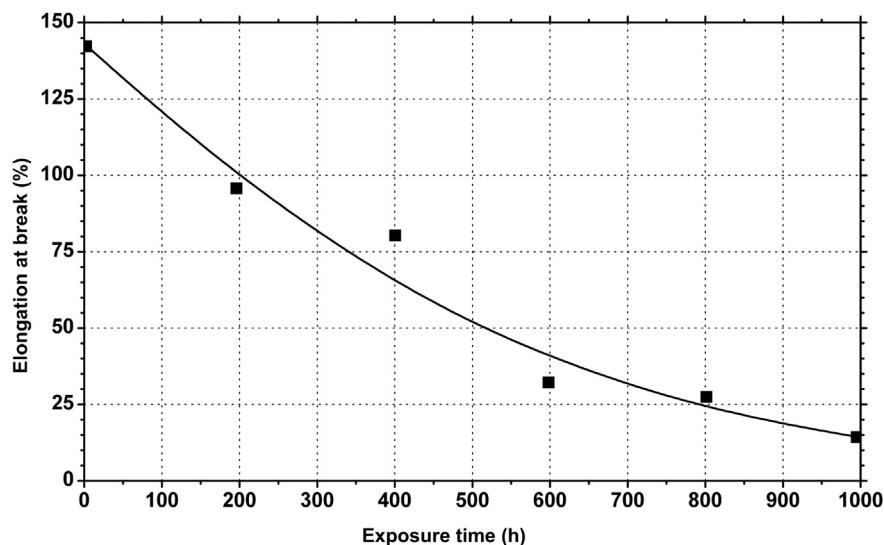


Figure 5.44 Degradation of tensile elongation by sunshine type Weather-Ometer® (thickness 200 µm) of Mitsubishi Engineering-Plastics lupilon/Novarex PC.¹⁹



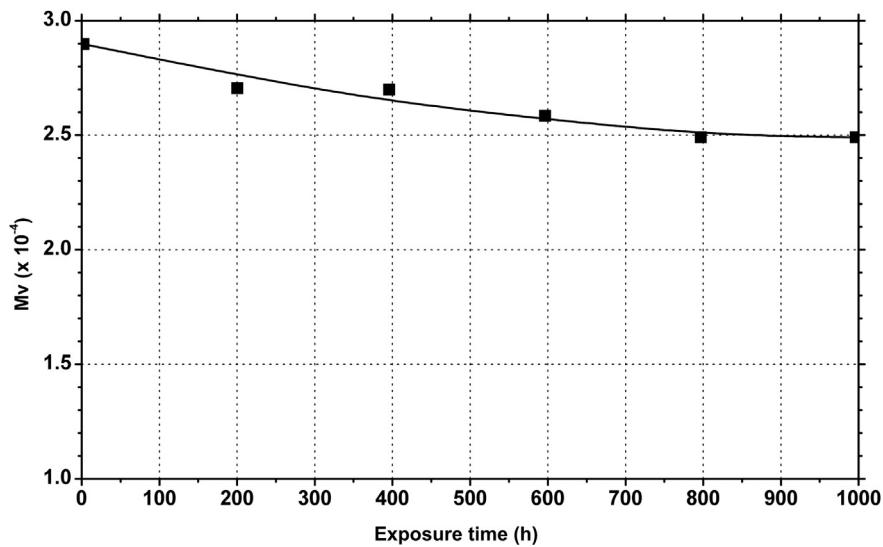


Figure 5.45 Degradation of melt viscosity by sunshine type Weather-Ometer® (thickness 200 μm) of Mitsubishi Engineering-Plastics Lupilon/Novarex PC.¹⁹

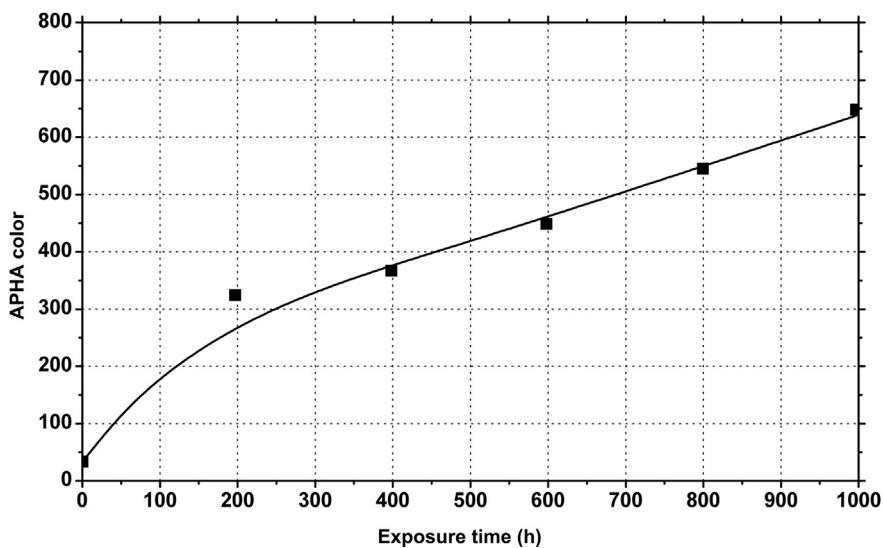


Figure 5.46 Degradation of APHA (color standard named for the American Public Health Association and defined by ASTM D1209) color by sunshine type Weather-Ometer® (thickness 200 μm) of Mitsubishi Engineering-Plastics Lupilon®/Novarex PC.¹⁹

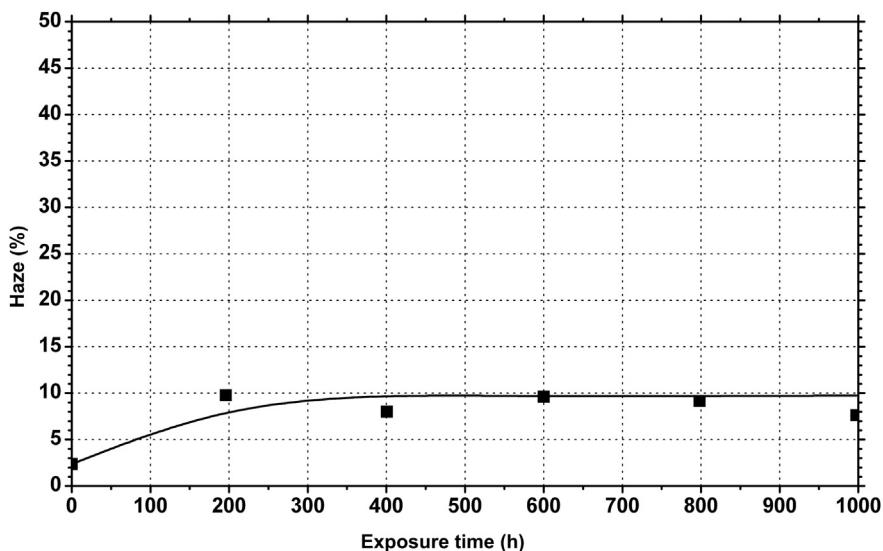


Figure 5.47 Degradation of haze by sunshine type Weather-Ometer® (thickness 200 μm) of Mitsubishi Engineering-Plastics Lupilon®/Novarex PC.¹⁹

Figure 5.48 Light transmission vs. weathering exposure for Evonik Cyrolon® PC.²⁷ Comparing the weatherability of ACRYLITE Sheet vs. polycarbonate sheet, CYRO Industries, 2005. Note: Test method: ASTM D1003.

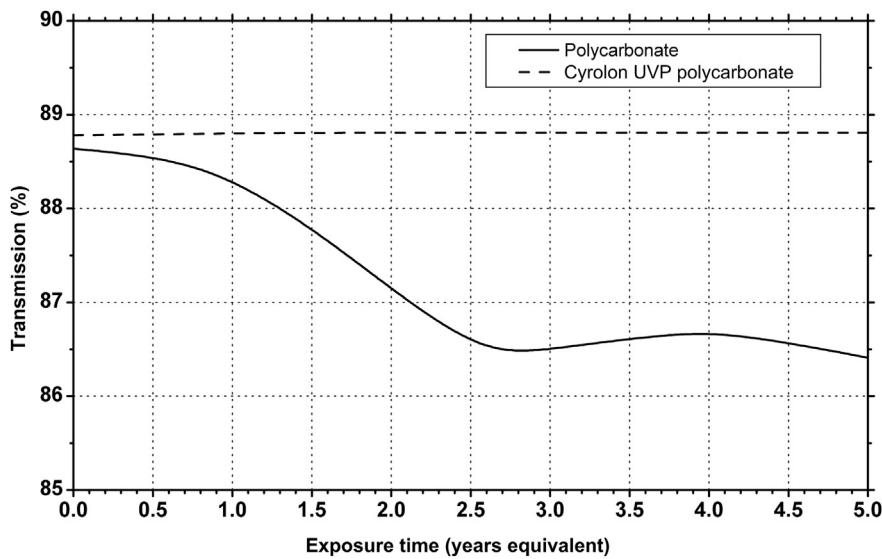


Figure 5.49 Color change, ΔE , of pigmented GE plastics Cycoloy® C1100 PC/ABS after accelerated UV exposure as per SAE J1885 (Atlas Ci65X-W) and DIN75202 (Xenon 450).²¹

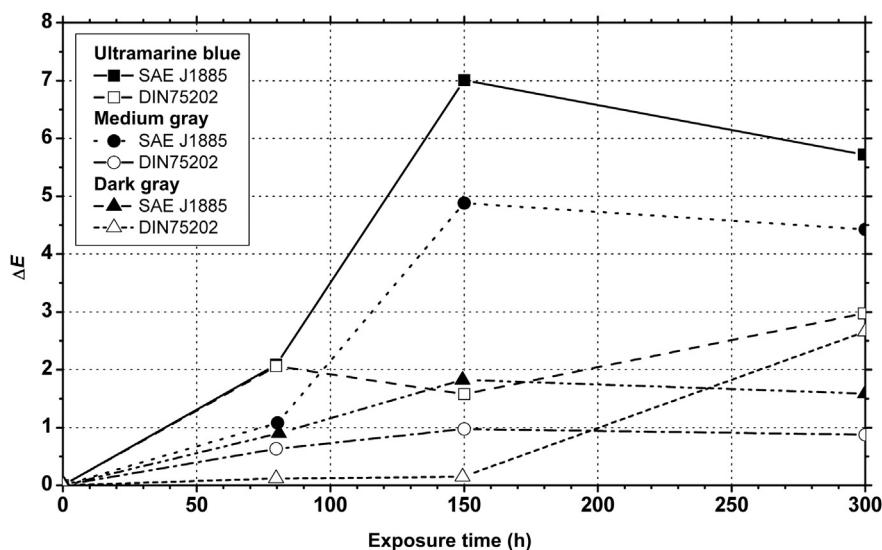
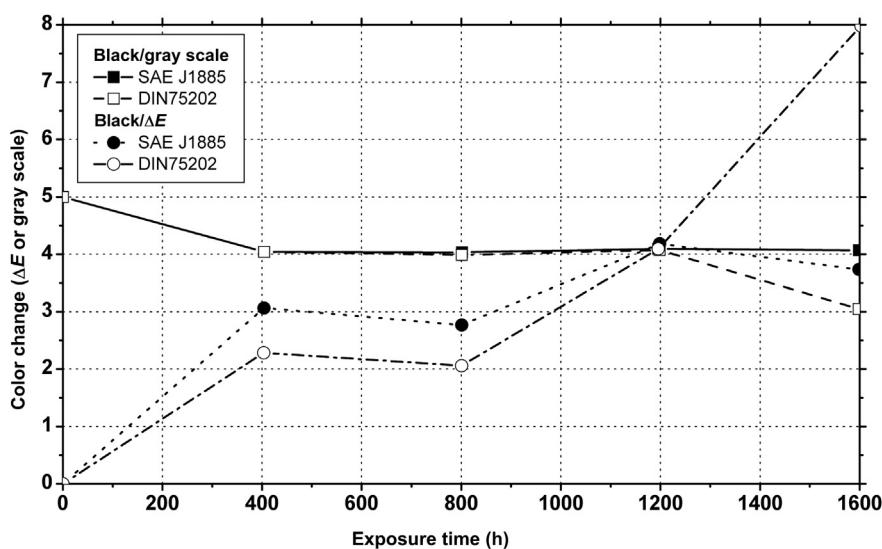


Figure 5.50 Color change, ΔE , of pigmented GE plastics Cycoloy® C1100 PC/ABS after accelerated UV exposure as per SAE J1885 (Atlas Ci65X-W) and DIN75202 (Xenon 450).²¹



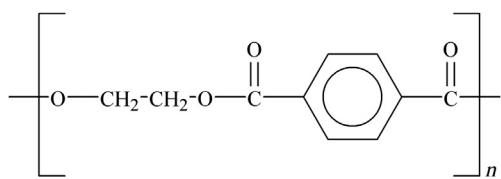


Figure 5.51 Chemical structure of polyethylene terephthalate (PET) polyester.

photo-Fries rearrangement.” This process is shown in Fig. 5.32.

Humidity on its own does not affect PC much, but in conjunction with UV exposure it affects the balance of the photo-Fries reaction vs. the photooxidation reaction typical of polyesters. Products of photodegradation include hydroperoxides, free radicals, chain scissions, cross-links, hydroxyl groups, carbonyl groups, ethers and unsaturations. This leads to embrittlement, surface erosion, loss of gloss, haze, discoloration and photobleaching.

PC sheet and injection molded parts may have a variety of coatings, including a range of hardcoats that enhance weathering, scratch and abrasion resistance.

Stabilization:

UVA: such as 2-hydroxy-4-octyloxybenzophenone.

Screeners: such as zinc oxide.

Phenolic antioxidant: such as 2-(1,1-dimethyl-ethyl)-6-[[3-(1,1-dimethyl-ethyl)-2-hydroxy-5-methylphenyl] methyl-4-methylphenyl acrylate.

Phosphite: such as tris (2,4-di-tert-butylphenyl) phosphite.

Optical brightener: such as 2,2'-(2,5-thiophenediyl)bis(5-tert-butylbenzoxazole).

Capped PC: surface layer made out of polymethyl methacrylate (PMMA) with 10 wt% biphenyl-substituted triazine for glazing applications.

Tinuvin® 234, a benzotriazole UV absorber, is well adapted to the UV stabilization of PC due to its low volatility, good initial color and compatibility with PC. To achieve the highest possible resistance to fading and weathering, Tinuvin® 1577, a UV absorber, may be used. This product is particularly recommended for use in coextruded PC sheets.¹⁴

Manufacturers and trade names: Bayer MaterialScience Makrolon®, Dow Calibre™

Data for PC plastics are found in Tables 5.7–5.12 and Figs 5.33–5.50.

5.4.1 Polycarbonate Blends

Weathering Properties: Cycloy® resins exhibit excellent UV stability. Slight color change and loss

Table 5.13 Tensile Strength and Elongation Retained after Arizona Outdoor Weathering of DuPont Rynite® 545 NC10, Rynite® 545 BK504, and Rynite® 935 BK505²²

Material Grade	Rynite 545 NC10					Rynite 545 8K504				Rynite 935 BK505		
Features	Natural Resin				Black Color				Black Color, Low-Warp Grade			
Material Composition												
Glass Fiber Reinforcement	45%	45%	45%	45%	45%	45%	45%	45%				
Mica/Glass Fiber Reinforcement									35%	35%	35%	35%
Exposure Conditions												
Exposure Time (Days)	182	365	730	1095	182	365	730	1095	182	365	730	1095
Properties retained (%)												
Tensile Strength	98	88	87	82	94	97	94	90	100	100	100	97.5
Elongation	82	77	73	68	83	94	89	78	100	94	94	76

Note: (1) 45° south.

Table 5.14 Tensile Strength and Elongation Retained after Arizona Outdoor Weathering of DuPont Rynite® 530 NC10 and Rynite® 530 BK503²²

Material Grade	Rynite 530 NC10				Rynite 530 BK503			
Features	Natural Resin				Black Color			
Material Composition								
Glass Fiber Reinforcement	30%	30%	30%	30%	30%	30%	30%	30%
Exposure Conditions								
Exposure Time (days)	182	365	733	1095	182	365	730	1095
Properties Retained (%)								
Tensile Strength	100	98	90	87	98	100	98	98
Elongation	85	88	77	73	91	96	96	83

Note: (1) 45° south.

Table 5.15 Tensile Strength and Elongation Retained after Florida Outdoor Weathering of DuPont Rynite® 530 NC10 and Rynite® 530 BK503²²

Material Grade	Rynite 530 NC10				Rynite 530 BK503			
Features	Natural Resin				Black Color			
Material Composition								
Glass Fiber Reinforcement	30%	30%	30%	30%	30%	30%	30%	30%
Exposure Conditions								
Exposure Time (Days)	182	365	730	1095	182	365	730	1095
Properties Retained (%)								
Tensile Strength	98	92	82	76	100	91	91	96

Note: (1) 45° south.

Table 5.16 Tensile Strength and Elongation Retained after Florida Outdoor Weathering of DuPont Rynite® 545 NC10 and Rynite® 545 BK504²²

Material Grade	Rynite 545 NC10				Rynite 545 BK504			
Features	Natural Resin				Black Color			
Material Composition								
Glass Fiber Reinforcement	45%	45%	45%	45%	45%	45%	45%	45%
Exposure Conditions								
Exposure Time (Days)	182	365	730	1095	182	365	730	1095
Properties Retained (%)								
Tensile Strength	89	84	75	72	88	90	91	91

Note: (1) 45° south.

Table 5.17 Tensile Strength and Elongation Retained after Arizona EMMA and EMMAqua® Weathering of DuPont Rynite® 530 NC10, Rynite® 530 BK503, Rynite® 545 NC10, and Rynite® 545 BK504²²

Rynite Material Grade	530 NC10	530 BK503	545 NC10	545 BK504	530 NC10	530 BK503	545 NC10	545 BK504
Features	Natural Resin	Black Color						
Material composition								
Glass Fiber Reinforcement	30%	30%	45%	45%	30%	30%	45%	45%
Exposure Conditions								
Exposure Apparatus	EMMA				EMMAqua®			
Total Radiation (Langleyes)	500,000				500,000			
Properties retained (%)								
Tensile Strength	100	100	92	93	100	100	92	93
Elongation	85	87	73	89	81	87	73	94

Exposure Note: (1) 150,000 Langleyes is approximately equal to one year.

Table 5.18 Tensile Strength, Tensile Strain and Tear Resistance Polyethylene Terephthalate of Foil before, during and after Two Years of Exposure to Natural Weathering²³

Exposure time (Months)	Tensile Strength Extrusion Direction (MPa)	Tensile Strength Perpendicular Direction (MPa)	Elongation at Break Extrusion Direction (%)	Elongation at Break Perpendicular Direction (%)	Tear Resistance Extrusion Direction (daN/cm)	Tear Resistance Perpendicular Direction (daN/cm)
0	128	183	154	97	375	380
Continental Climate (Nikinci)						
6	59.9	88.1	4.9	4.2	196	256
12	57.1	72.8	3.8	3.2	7	9
18	41.9	64.6	2.7	2.9	5	6
24	22.3	24.9	2.8	2.3	4	4
Continental Climate (Nikinci)						
6	52.6	67.9	3.0	2.9	62	105
12	51.2	61.6	3.5	2.9	7	7
18	39.6	61.1	2.8	2.5	5	5
24	20.7	21.6	2.6	2.2	4	4

Table 5.19 Color, Thickness and Flexibility at Low Temperature and Integral Light Transparency of Polyethylene Terephthalate Foil before, during and after Two Years of Exposure to Natural Weathering²³

Exposure Time (Months)	Color	Thickness (mm)	Flexibility at Low Temperature (-30°C)	Integral Light Transparency (%)
0	No color	0.14	No break	89
Continental Climate (Nikinci)				
6	No color	0.14	No break	89
12	No color	0.14	No break	89
18	No color	0.14	No break	87
24	No color	0.14	Break	87
Continental Climate (Nikinci)				
6	No color	0.14	No break	87
12	No color	0.14	No break	87
18	No color	0.14	No break	86
24	No color	0.14	Break	86

Table 5.20 Effect of Accelerated Weathering on the Retention of Original Physical Properties of DuPont Rynite® PET Resins²⁴

Exposure	Rynite® 530 NC010	Rynite® 530 BK503	Rynite® 545 NC010	Rynite® 545 BK504
EMMA—500,000 Langleys^a				
Tensile Strength	100	100	92	93
Elongation	85	87	73	89
EMMAqua®—500,000 Langleys^a				
Tensile Strength	100	100	92	93
Elongation	81	87	73	94

Note: (1) EMMA = Equatorially mounted mirror assisted. (2) EMMAqua® = EMMA assisted with water.

^a150,000 Langleys = One year.

of mechanical properties can result after long-term exposure.²¹

Stabilization: Tinuvin® 234 protects PC blends from the discoloration associated with exposure to UV light.¹⁴

5.5 Polyethylene Terephthalate

Polyethylene terephthalate (PET) polyester is the most common thermoplastic polyester and is often

called just “polyester”. This often causes confusion with the other polyesters in this chapter. PET exists both as an amorphous (transparent) and as a semicrystalline (opaque and white) thermoplastic material. The semicrystalline PET has good strength, ductility, stiffness and hardness. The amorphous PET has better ductility but less stiffness and hardness. It absorbs very little water. Its structure is shown in Fig. 5.51.

Weathering Properties: Rynite® 530 NC10 and BK503 and Rynite® 545 NC10 and BK504 resins

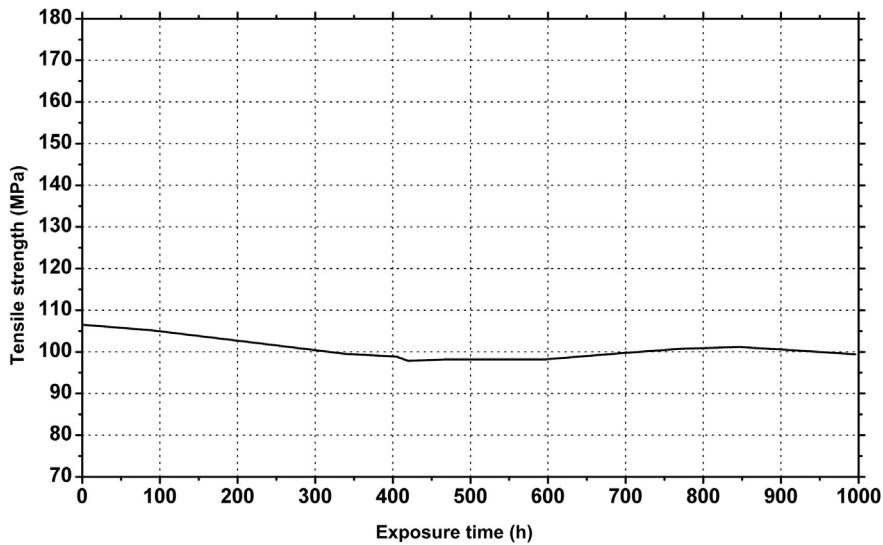


Figure 5.52 Tensile strength after sunshine Weather-Ometer® exposure of PET.²⁵

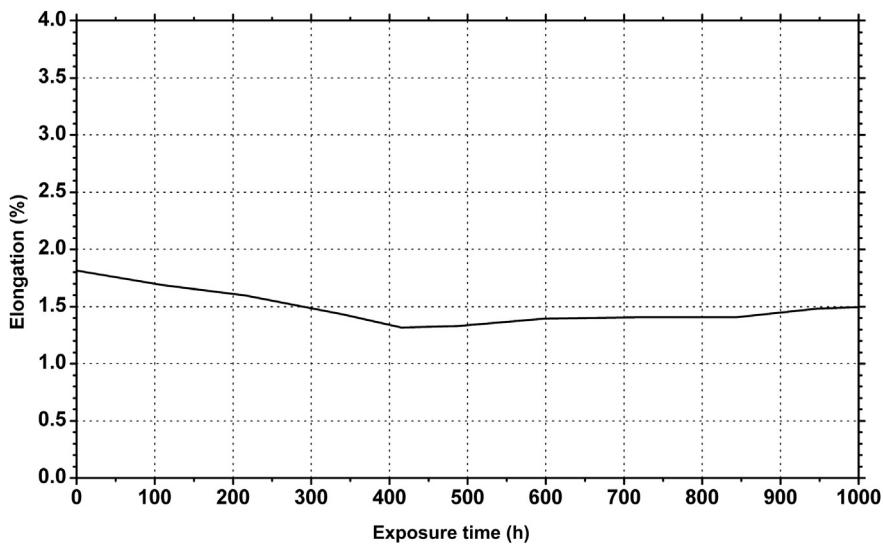


Figure 5.53 Elongation after sunshine Weather-Ometer® exposure of PET.²⁵

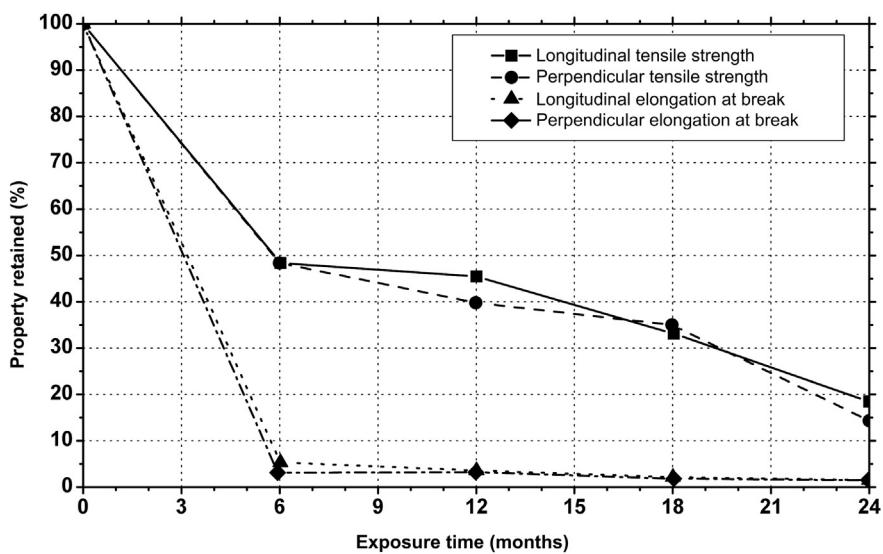


Figure 5.54 Changes of tensile strength and elongation at break of PET in longitudinal and perpendicular directions in continental area (Nikinci).²³

Figure 5.55 Changes of tensile strength and elongation at break of PET in longitudinal and perpendicular directions in marine area (Kumbor).²³

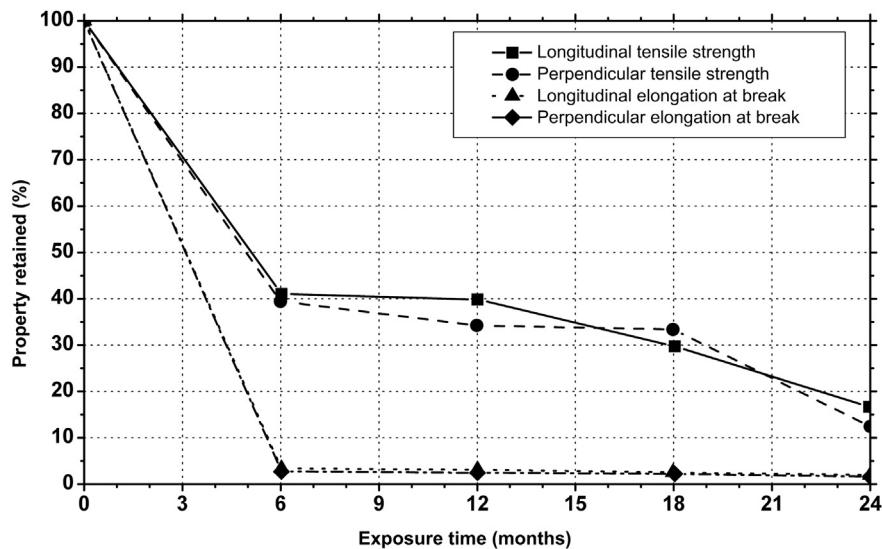


Figure 5.56 Changes of tear resistance of PET in longitudinal and perpendicular directions and integral light transparency as a function of exposure time in continental area (Nikinci).²³

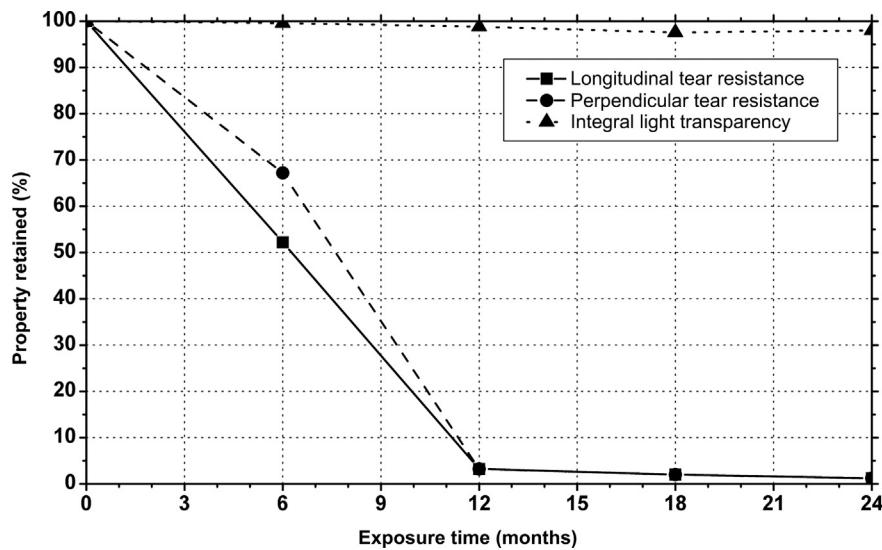
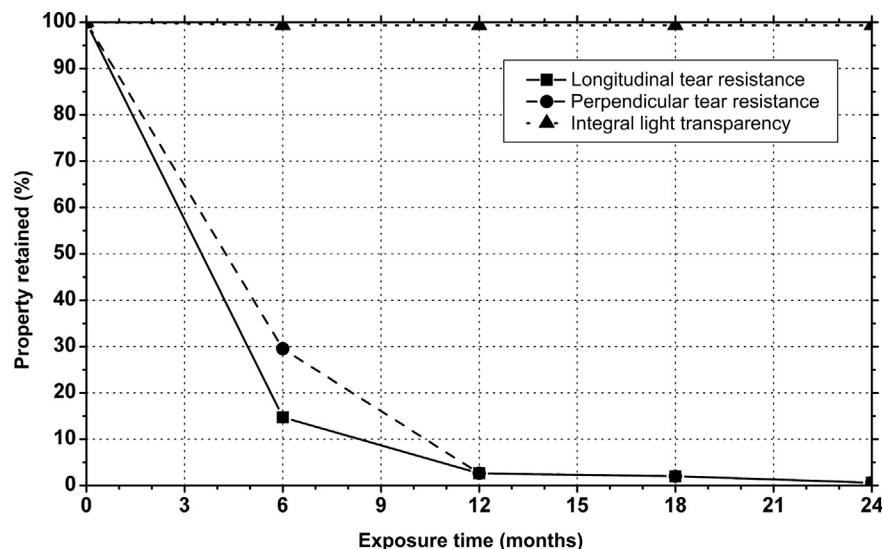


Figure 5.57 Changes of tear resistance in longitudinal and perpendicular directions and integral light transparency as a function of exposure time of PET in marine area (Kumbor).²³



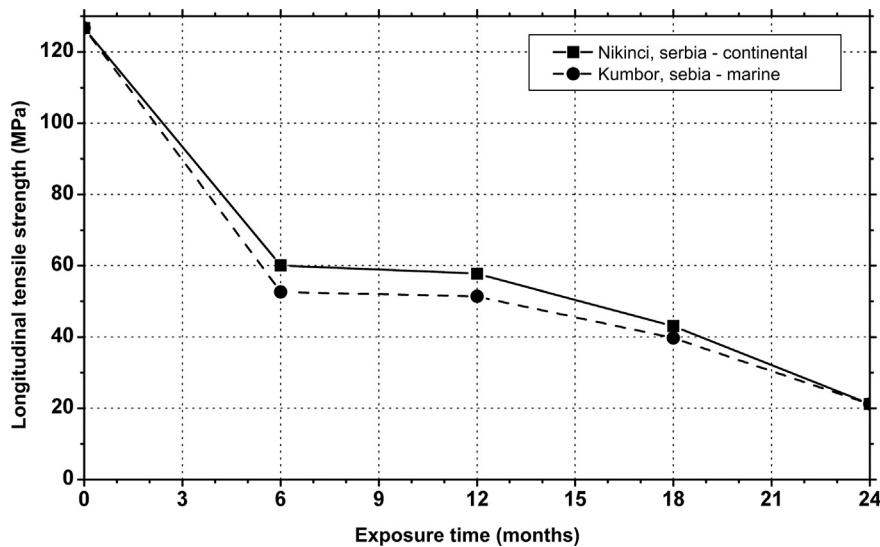


Figure 5.58 Changes of longitudinal tensile strength vs. exposure time of PET in continental (Nikinci) and marine areas (Kumbor).²³

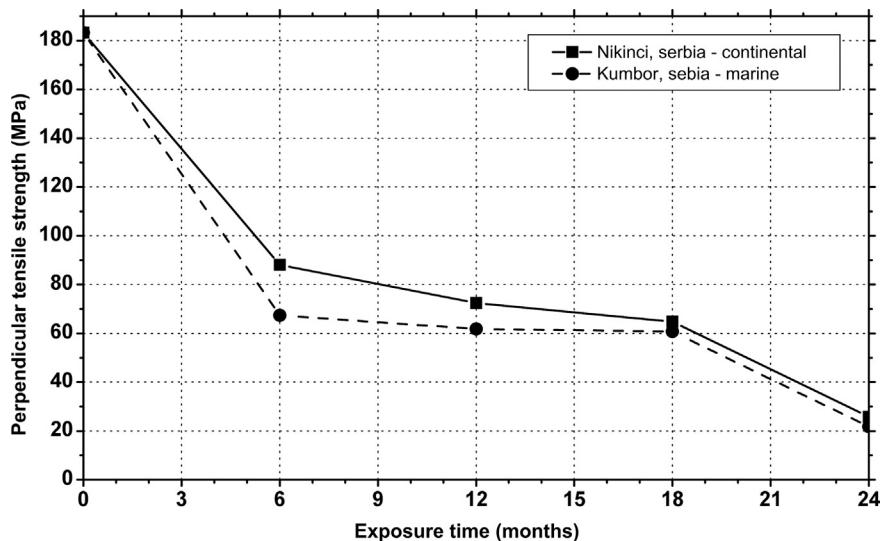


Figure 5.59 Changes of perpendicular tensile strength vs. exposure time of PET in continental (Nikinci) and marine areas (Kumbor).²³

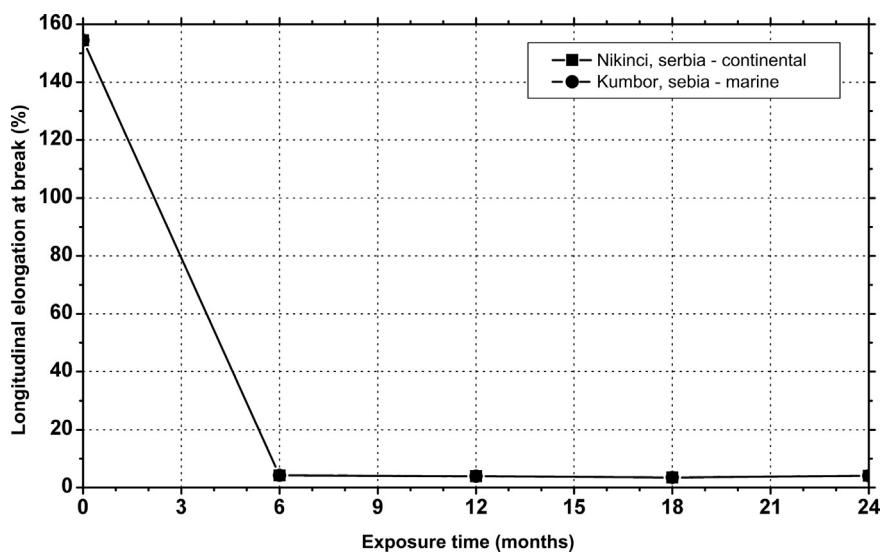


Figure 5.60 Changes of longitudinal tensile strain vs. exposure time of PET in continental (Nikinci) and marine areas (Kumbor).²³

Figure 5.61 Changes of perpendicular tensile strain vs. exposure time of PET in continental (Nikinci) and marine areas (Kumbor).²³

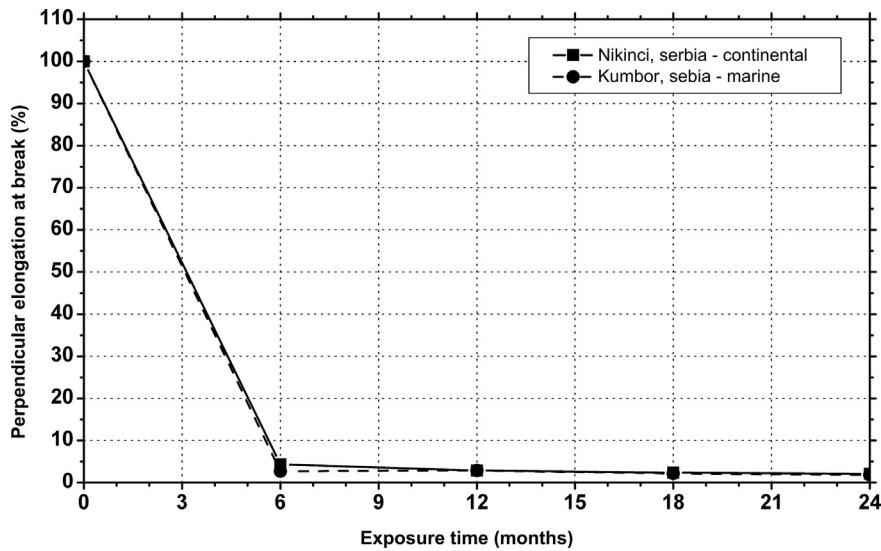


Figure 5.62 Changes of longitudinal tear resistance vs. exposure time of PET in continental (Nikinci) and marine areas (Kumbor).²³

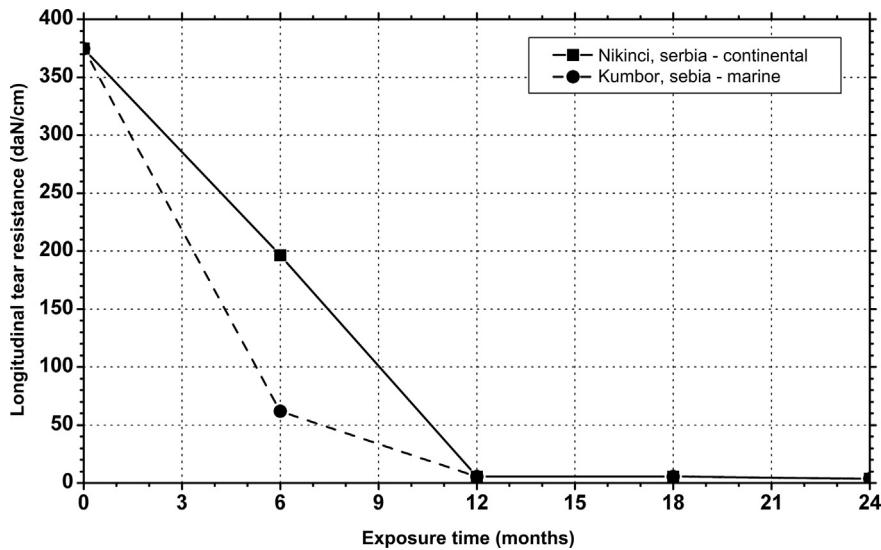
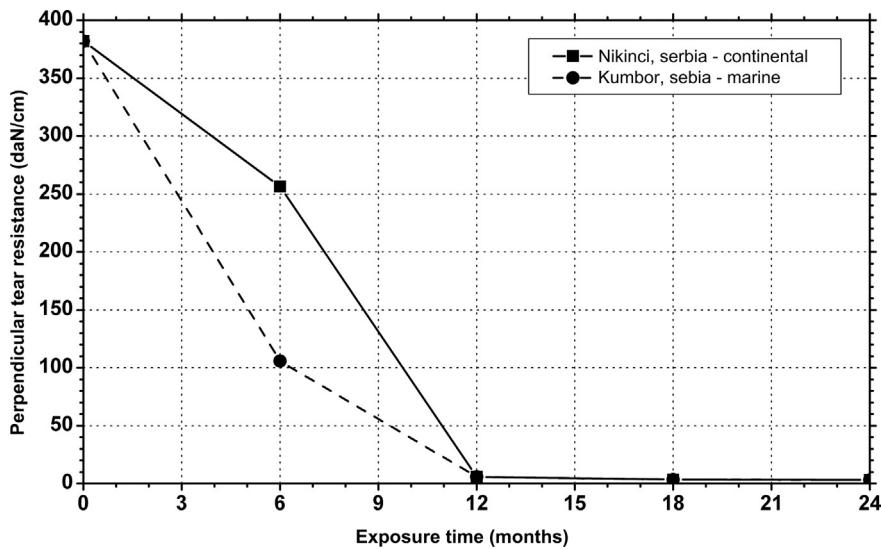


Figure 5.63 Changes of perpendicular tear resistance vs. exposure time of PET in continental (Nikinci) and marine areas (Kumbor).²³



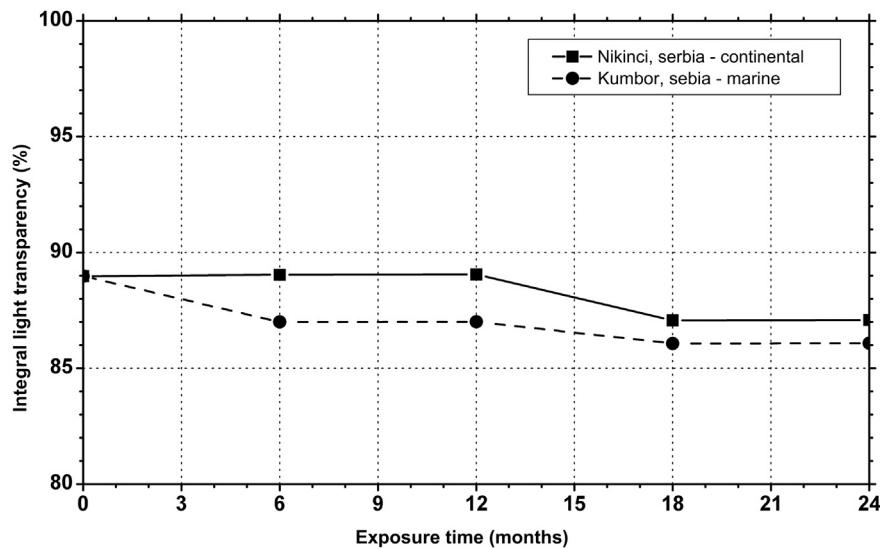


Figure 5.64 Changes of integral light transparency vs. exposure time of PET in continental (Nikinci) and marine areas.²³

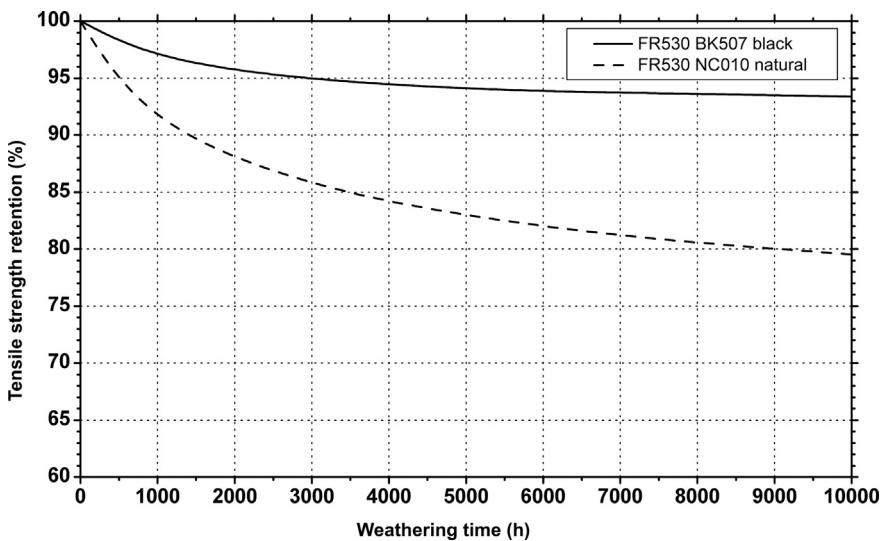


Figure 5.65 Percent retention of original tensile strength after exposure in X-W Weather-Ometer of DuPont Rynite® FR530 PET resins.²⁴ Note: Rynite® FR530 is 30% glass reinforced, flame retardant, modified polyethylene terephthalate resin approved by UL as UL94V-0 at 0.35 mm.

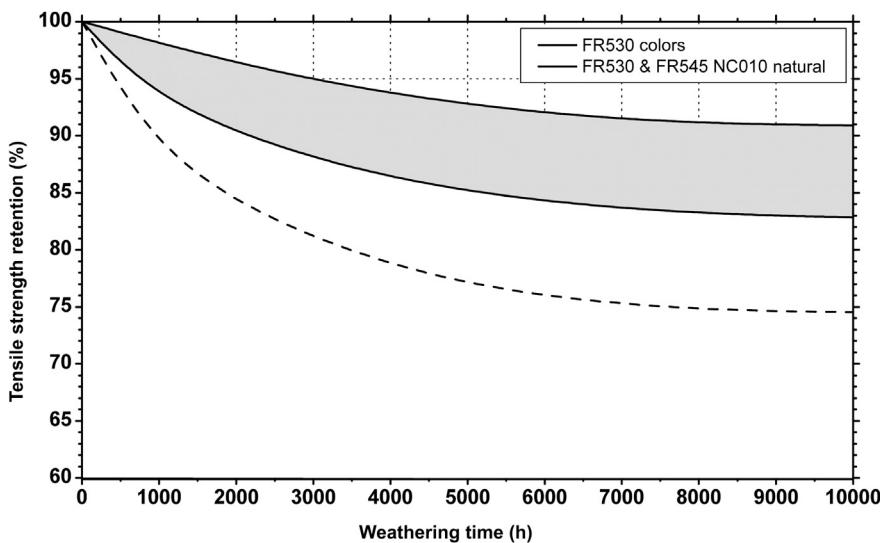


Figure 5.66 (Figure 5.72) Percent retention of original tensile strength after exposure in X-W Weather-Ometer DuPont Rynite® PET resins.²⁴ Note: Rynite® FR530 is 30% glass reinforced, flame retardant, modified polyethylene terephthalate resin approved by UL as UL94V-0 at 0.35 mm; Rynite® FR545 is 45% glass reinforced.

Figure 5.67 Retention of tensile strength after 45° south outdoor Florida weathering of DuPont Rynite® PET resins.²⁴

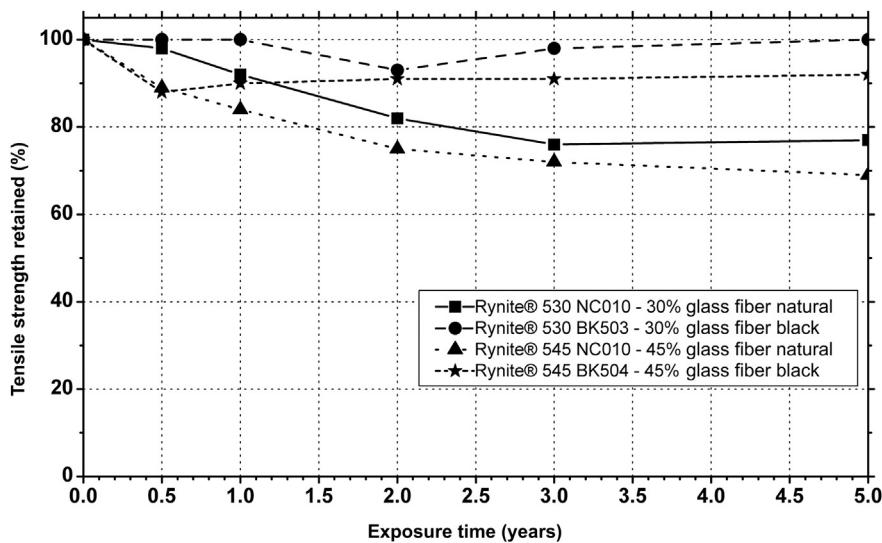


Figure 5.68 Retention of elongation after 45° south outdoor Florida weathering of DuPont Rynite® PET resins.²⁴

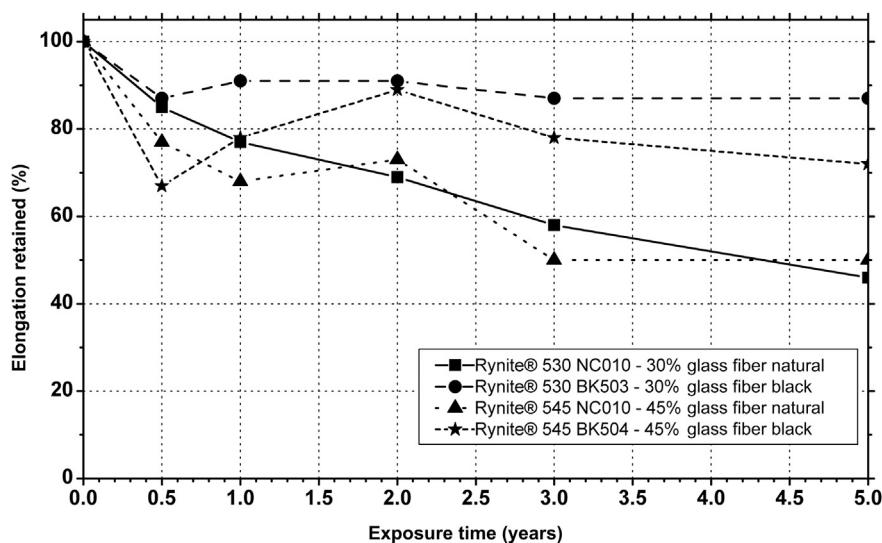
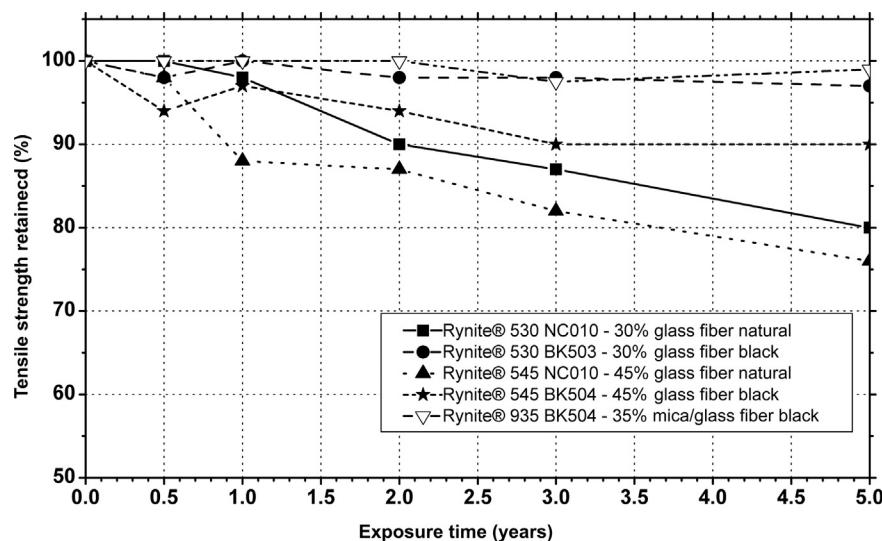


Figure 5.69 Retention of tensile strength after 45° south outdoor Arizona weathering of DuPont Rynite® PET resins.²⁴



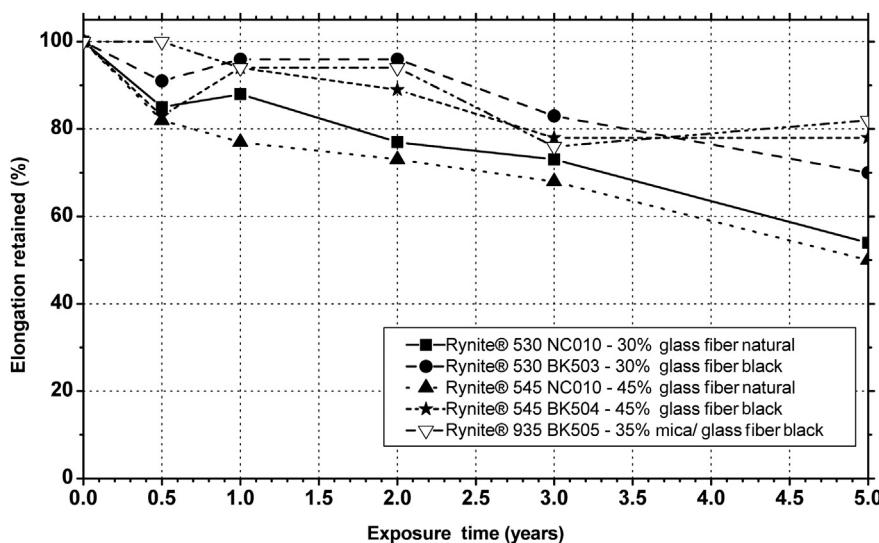


Figure 5.70 Retention of elongation after 45° south outdoor Arizona weathering of DuPont Rynite® PET resins.²⁴

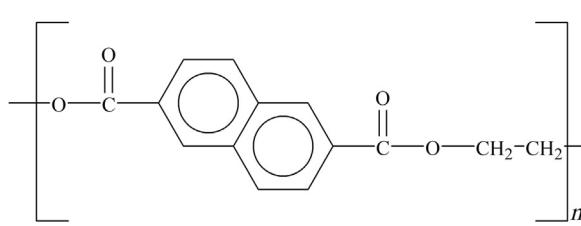


Figure 5.71 Structure of polyethylene naphthalate (PEN).

have been exposed outdoors in Florida and Arizona facing 45° south for three years. The data for these samples indicate that the resins have retained over 72% of their initial tensile strength and over 50% of their initial elongation. The compositions containing carbon black had higher property retention. After three years, all the test samples were slightly “etched”.²²

After 500,000 langleys of exposure in the Equatorial Mount with Mirrors (EMMA) and EMMA with water spray (EMMAqua) environments, Rynite® 530 NC10 and BK503 and Rynite® 545 NC10 and BK504 resins maintained over 90% of their original tensile strength and 73% of their original elongation properties. The EMMA and EMMAqua environments have similar effects on the properties of the Rynite® 530 and Rynite® 545 resins. All test specimens had reduced gloss levels after exposure. On an average, samples exposed in Arizona received approximately 150,000 langleys of sunlight per year. These tests correspond to about 3.3 years of natural weathering in Arizona.²²

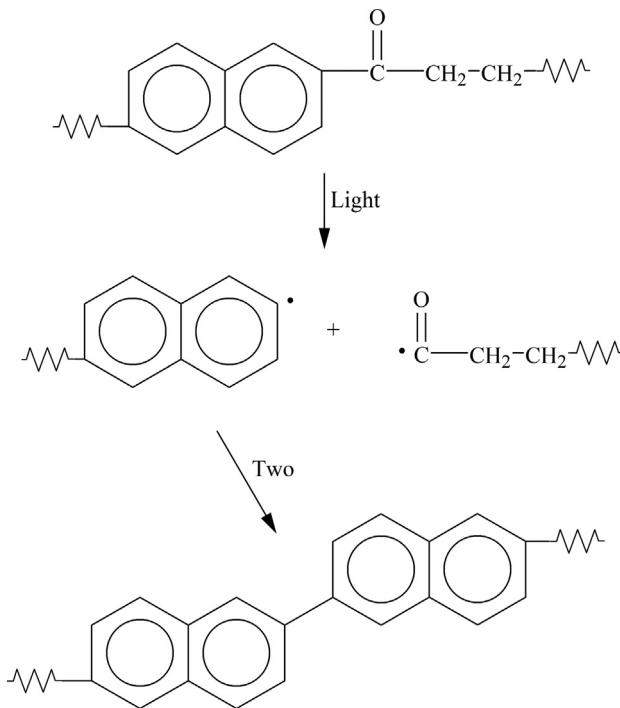


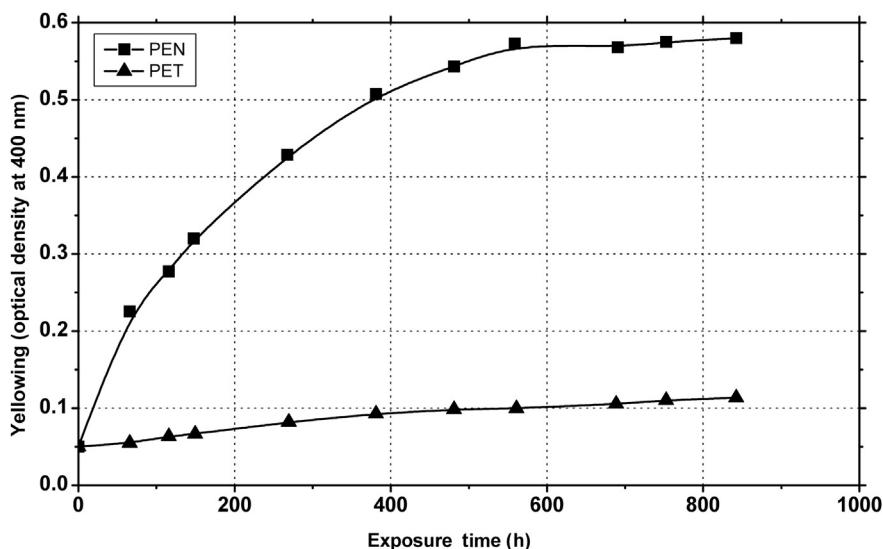
Figure 5.72 Photolysis leading to cross-linking in poly(ethylene naphthalate).

Stabilization: See general polyester stabilizers in the introduction of this chapter.

Manufacturers and trade names: DuPont Rynite®, DuPont Teijin Films™ Mylar® and Melinex®, Mitsubishi Polyester Film Hostaphan®.

Applications and uses: bottles for soft drinks and water, food trays for oven use, roasting bags, audio/video tapes, mechanical components.

Figure 5.73 Yellowing of PEN and PET as measured by optical density at 400 nm vs. exposure time in SEPAP 12/24.²⁶



Data for PET plastics are found in Tables 5.13–5.20 and Figs 5.52– 5.70.

5.6 Polyethylene Naphthalate

Poly(ethylene 2,6-naphthalene dicarboxylate) (PEN) is the condensation product of 2,6-naphthalene dicarboxylic acid and ethylene glycol. PEN is similar to PET but has better temperature resistance. The structure of this polyester is shown in Fig. 5.71.

Weathering: The photolysis of poly(ethylene naphthalate) leads to cross-linking of the polymer as shown in Fig. 5.72. The cross-linked structures cause severe discoloration. This is one major difference in exposure behavior of poly(ethylene naphthalate) when compared to most other polyesters. The other major difference is in UV absorption spectrum. PBT and PET absorb in the short UV (up to 325 nm), and PEN absorbs in the entire UV range (290–390 nm) making it very vulnerable to radiation. Other reactions typical of polyesters also apply to PEN.

Manufacturers and Trade names: DuPont™ Teijin Films TEONEX®, Eastman Eastar®, Shell HiPertuf.

Applications and uses: plastic beer bottles, baby food jars.

Data for PEN plastics are found in Fig. 5.73.

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