Durability Testing for Retroreflective Sheetings

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Although there is considerable published research pertaining to the usefulness of or problems associated with durability testing of polymers or paints and coatings, there is little published work specifically addressing durability testing for retroreflective sheetings. The simulation of exterior exposure stresses in artificial accelerated tests is discussed and measurements of the spectral power distribution of light sources commonly used in accelerated tests are compared with that for sunlight. Two exposure experiments are described that show how poor simulation of exterior stresses can lead to reversals between predictions from artificial tests and exterior exposures. Variability in exterior exposures is illustrated by results from a single set of sheetings exposed at different times at the same site. Experiments using a single lot of retroreflective sheeting exposed in identical devices all operating the same test cycle are used to quantify the variability associated with artificial accelerated testing. Artificial accelerated and exterior exposures of a series of eight lots of retroreflective sheeting are compared and show that there are large differences in sheeting rank performance between the artificial accelerated tests and 5-year exterior exposures. An experiment comparing several exposure orientations for a model retroreflective sheeting indicated a 2:1 increase in degradation rate for a 45 degree angle or solar tracking exposures relative to the vertical.

Retroreflective sheetings are complex multilayer composite products in which deterioration of performance can be caused by any of a number of mechanisms. Typical failure modes are

- Destruction of the metallic reflector coat;
- Disruption or distortion of the optical elements within the sheeting, making retroreflection of incoming light less efficient;
- Degradation or destruction of the outermost polymer layer;
- Fading of dyes or pigments used to produce appropriate color in the sheeting or screen-printed graphics; and
- Failure of bonds between layers, causing separation or delamination of the composite.

The type of failure or degradation can depend on the type of sheeting being tested (enclosed lens, encapsulated lens, or cube corner) and also on the composition of the individual layers within the sheeting construction. Failures can be initiated or accelerated by a particular combination of environmental stresses that may only occur in certain geographical locations or climates. For example, in some environments the combined effects of sunlight and moisture initiate reactions that can cause corrosion of the metallic reflector coat. Other climates may produce disruptions of the optical path in the sheeting by repeated expansions and contractions of polymer layers during cycling between wet and dry or hot and cold conditions.

Scientists involved in development of materials for exterior applications and those involved with setting specifications have long desired to assess durability by using results from artificial accelerated testing ("machine weathering") rather that waiting for results from long-term exterior exposures. Although there are numerous studies in the literature on the establishment of "acceleration factors" equating *X* hours in an artificial accelerated test to *Y* months' exterior exposure, there are several very important reasons why such relationships are meaningless, namely, variability in exterior climates, poor replication of exterior stresses in artificial tests, and variability in the accelerated testing devices. In order to evaluate how these problems affect durability tests for retroreflective sheeting, a series of exposure experiments was conducted. In addition, the spectral power distributions (SPD) of light sources used for artificial accelerated tests were measured and compared with the SPD of sunlight. The experiments and how the results can affect durability testing protocols for retroreflective sheeting are described in the following sections.

EXPOSURE AND EXPERIMENTS

All retroreflective sheeting lots used in the exposure experiments were prepared in the 3M Traffic Control Materials Division laboratory or as part of production experiments conducted in 3M manufacturing plants. Pressure-sensitive adhesives were used in all lots. (The durability data presented here should not be taken as representative of the performance of any commercially available 3M retroreflective sheeting product.) Artificial accelerated exposures were conducted in the Weathering Services Laboratory of 3M's Analytical and Properties Research Lab. The artificial exposure tests used are described in Table 1.

Outdoor exposures were conducted per ASTM Standard Practice G7 at sites in Miami and Phoenix. Florida exposures were on open racks, whereas Arizona exposures were conducted with samples mounted on plywood-backed racks.

Sheetings were applied to 5052H33 (0.025 in. thick) aluminum panels that were chromate treated per ASTM B449, Class 2. Replicate samples of each lot tested were used for all exposure tests. Table 2 summarizes the exposure tests and number of replicates used for each sheeting lot or series.

Before exposure and after each exposure increment, samples were tested for retroreflectivity (coefficient of retroreflectance at −4-degree entrance angle, 0.2-degree observation angle) per ASTM E810. Where indicated, 60-degree

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TABLE 1 ARTIFICIAL ACCELERATED EXPOSURE TEST CONDITIONS

ASTM G23-84, Type E, Method 1		
	Filtered (#7058 Corex) open flame carbon arc	
	Cycle:	102 minutes light only
		18 minutes light plus water spray
		63°C black panel temperature
ASTM G26-84, Type B		
	Water cooled 6500 watt xenon burner	
	Borosilicate inner and outer filters	
	Cycle:	102 minutes light only
		18 minutes light plus water spray
		63°C black panel temperature
ASTM G53-84		
	FS-40 UVB fluorescent lamps	
	Cycle:	4 hours UV at 60°C black panel temperature
		4 hours condensation at 50°C black panel temperature

gloss and yellowness indexes were tested per ASTM D523 and ASTM D1925, respectively. Results are reported as the mean of tests made on replicate panels.

Irradiance measurements were made using a model DG-52 spectroradiometer system from EG&G Gamma Scientific equipped with an NM9H double grating monochromator with 2-nm resolution and a model 50B cosine receptor. The spectroradiometer was calibrated with deuterium- and tungsten-calibrated reference lamps traceable to the National Bureau of Standards. Measurements were made at 2-nm increments using the average of 200 individual readings. The cosine receptor was positioned at the sample plane in a fluorescent ultraviolet (UV) device while measurements in the carbon and xenon arc devices were made with the cosine receptor positioned near the sample plane using a specially modified door. In all cases, measurements were made at the center of the allowed exposure area. Irradiance at the sample plane for the carbon and xenon arc devices was obtained by multiplying the measured irradiance values by correction factors calculated using the inverse-square law, which accounts for the relative position of the cosine receptor and the sample plane. The solar spectral power distribution was obtained by Ohio Spectrographic Service from measurements made in Phoenix (clear sky, solar noon, summer solstice, cosine receptor mounted on an equitorial follow-the-sun motor drive, measurements made at 1-nm increments with 1-nm bandpass).

Measurements of black panel temperatures were made at the South Florida Test Service facility in Phoenix (Wittman), Arizona. Temperatures were continuously recorded on a strip chart for a 3-week period during April–May 1986. The black panels were 18-gauge steel coated with Rust-Oleum Bar-BQ Enamel®, oven dried for 8 hr and air dried for 1 week before use. The thermocouples were attached to the backs of the panels and were calibrated at 0° and 60°C. Measurements were made with the black panels mounted on 34- and 90-degree open backed racks.

RESULTS AND DISCUSSION

Exposure Stress Simulation

In an attempt to produce rapid results, artificial accelerated tests often use light sources that have significant emissions below the solar UV cutoff (290 nm). Figures 1 and 2 show results for UV spectral power distribution measurements made at the sample position in several artificial accelerated devices. One can easily see the differences between these light sources and sunlight. Figure 2 clearly shows the much higher irradiance levels for the artificial light sources at shorter wavelengths. It is this short-wavelength radiation that can produce rapid photodegradation that may not be representative and could overwhelm important degradation reactions that occur in exterior exposures.

In addition, water spotting is a persistent problem when water spray is used as a moisture source, even in systems where great care is taken to control dissolved solids. Cutrone (*1*) reported the formation of silica deposits on paint samples exposed in an accelerated test using water spray (per British Standard BS3900, part F3) and speculated that colloidal silica in the spray water was the cause. Even though water used in accelerated test devices at 3M is treated by being passed through a multistage deionizing system to remove particulates, anions, cations, and organic materials, silica deposits have been detected on retroreflective sheetings and other materials exposed in those devices. These deposits detract from appearance and

TABLE 2 SUMMARY OF EXPOSURE TESTS CONDUCTED

Sheeting Lot or Series	Number of Samples Tested	Description of Exposure Tests
Lots A and B	2	Carbon Arc (G23) and Fluorescent UV/ condensation (G53)
	2	12 month Florida 45°
	4	24 month Florida 45°
	6	36 month Florida 45°
	8	48 month Florida 45°
Lot C	3	Carbon Arc (G23), six units all using the same cycle, 3 replicate samples per unit
Lot D	3	Fluorescent UV/condensation (G53), four units all using the same cycle, 3 replicate samples per unit
Series I	18	Nine lots from a designed experiment evaluating formulation variations for a single type of sheeting. Two replicate samples for each lot. Florida 45° exposures.
Series II	2	Eight lots of retroreflective sheeting (enclosed lens, encapsulated lens and cube corner), 2 replicate samples of each lot used for all artificial accelerated tests (G23, G53, and G26)
	6	Six replicates for each of the eight lots were used for the five year Florida and Arizona exposures.
Series III	72	One lot of sheeting was used, 12 samples were sent out for each of the six exposure orientations. One sample was recalled each month for evaluation.

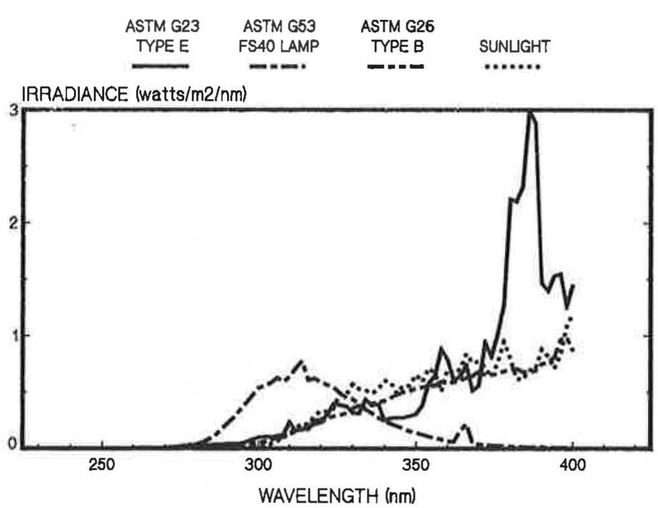

FIGURE 1 Representative spectral power distribution for light sources used in artificial accelerated exposure testing.

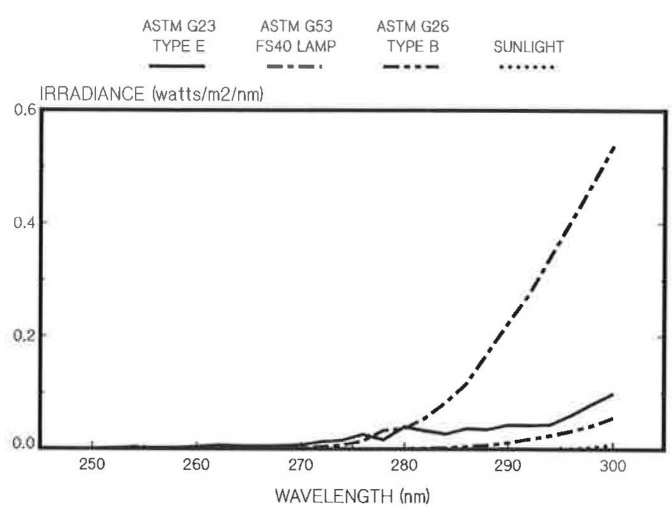

FIGURE 2 Representative short-wavelength UV power distributions for light sources used in artificial accelerated exposure testing.

can lead to unrealistic surface deterioration that does not occur in exterior exposures.

Furthermore, artificial accelerated testing may not subject samples to certain stresses that are very important in exterior exposures. Work by Yamaski (*2*) showed that materials exposed outdoors are wet between 21 and 35 percent of the time in humid continental climates such as Ottawa, Canada (45 degrees N latitude). Rain events account for only a small amount of the total wet time, so samples are wet with condensation or dew. Condensed moisture is fully saturated with oxygen, an essential element in polymer oxidation. Accelerated tests using water sprays do not control oxygen level in water and more probably simulate rain and not condensation.

Standard artificial accelerated tests do not expose retroreflective sheeting samples to the effects of acid dew or acid rain, industrial pollutants such as sulfur dioxide or ozone, or deicing salts used on roadways. Research has shown that the rate of aluminum corrosion is directly related to the deposition rate of sulfur dioxide and chloride ions (*3,4*). Increased degradation of polymers in the presence of relatively low sulfur dioxide concentrations has also been reported (*5,6*). Comparison of natural dew and rainwater showed dew to have over 2 times the level of sulfate ion and 16 times the chloride ion concentration as rainwater (*7*).

Results presented in Figures 3 and 4 show how sheeting performance can be misjudged when artificial accelerated tests fail to reproduce exterior exposure stresses. In Figure 3, retroreflective sheeting lot A shows relatively poor performance in the ASTM G23 or ASTM G53 artificial accelerated test cycles described previously, but shows excellent results after 48 months of Florida 45-degree exposures. Conversely, the same artificial accelerated exposures of reflective sheeting lot B (Figure 4) show very little brightness loss after 2,500 hr, whereas Florida 45-degree exposures produced rapid failure.

Variability in Exposure Tests

Exterior Tests

Differences in climate between locations as well as between seasons are well understood and need no further explanation.

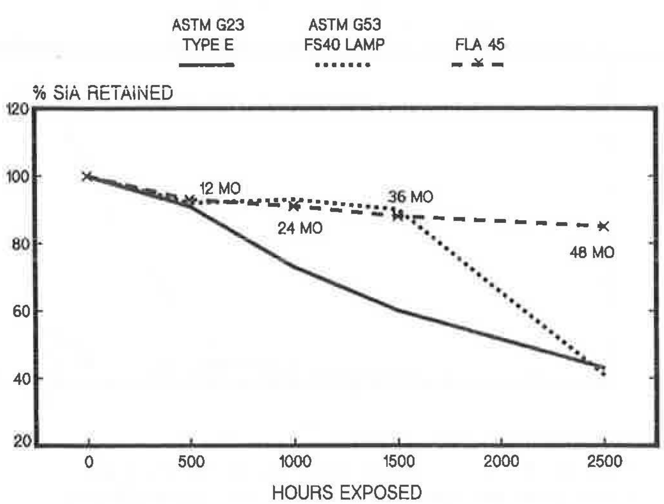

FIGURE 3 Comparison of results for artificial accelerated and Florida 45-degree exposures of retroreflective sheeting lot A.

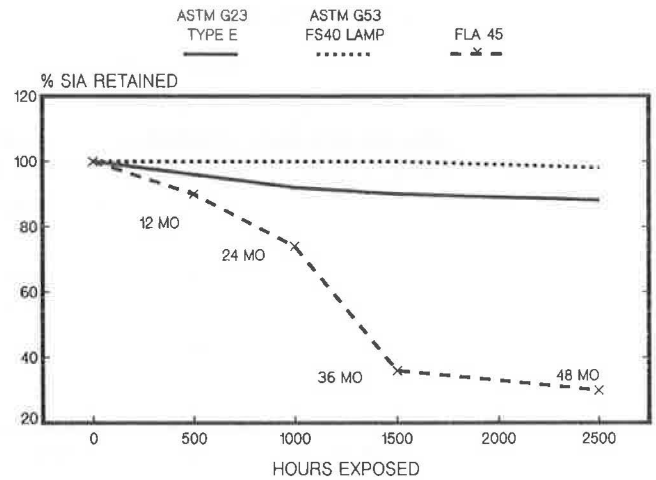

FIGURE 4 Comparison of results for artificial accelerated and Florida 45-degree exposures of retroreflective sheeting lot B.

What is important is the fact that virtually all exposure periods in any given location are unique. There can be significant differences in rate of failure for materials exposed at different times in the same location, as shown in the following example. A series of nine experimental retroreflective sheeting constructions, each a point from a designed experiment evaluating minor formulation changes for a single product, was exposed in Florida at a 45-degree angle for 12 months during 1982, with all nine constructions showing significant brightness loss. This set of samples was retired and a second exposure of an identical set from this same series was started in 1984 and continued for an additional 12 months in 1985–1986. The mode of failure (reflector coat oxidation) was the same for both sets of samples. Results on these identical samples and exposure times for these different dates are compared in Table 3 and show dramatic differences in failure rate. This is a clear example of how year-to-year differences in climate at the same location can affect results. Rate of failure may also depend on whether an exposure starts in the spring or fall of the year. Comparisons between materials should only be made by using a reference or control with all exposure evaluations. Use of multiyear exposures can improve reliability of results by averaging the effects of seasonal or year-to-year variability.

Artificial Accelerated Exposures

Artificial accelerated tests have traditionally been assumed to stress samples with temperature, light, and water in a much more consistent manner than exterior exposures. In essence, they have been almost considered to be analytical tests with a high degree of repeatability. However, recently published work indicates that results from artificial accelerated tests are highly variable. Blakey (*8*) reports that exposures of identical panels of a titanium-dioxide-pigmented air-dry alkyd paint in carbon arc units operating per British Standard BS3900, part F, produce very large machine-to-machine and within-machine differences. After 2,000 hr, 60-degree gloss values ranged from 17 to 60 for identical samples exposed in supposedly equivalent machines. Even larger variations were reported for a thermosetting acrylic formulation. The Association of Automobile Industries' Working Group on Test Methods for

Paints (*9*) reported results from a round-robin exposure study of a series of paints. Exposures were conducted in xenon arc devices all using the same test cycle and showed that after 2,000 hr, gloss values for identical paints varied by 50 percent of the mean for all machines.

In order to evaluate the degree of variability associated with artificial accelerated testing of retroreflective sheetings, two studies were conducted in which identical samples of retroreflective sheetings were exposed in equivalent machines using the same test conditions. The results for identical samples of retroreflective sheeting lot C exposed in six different XW Sunshine Carbon Arc Weatherometers operated per ASTM Standard Practice G23, Type E, Method 1 are shown in Figure 5. Each data point is the mean of three replicate samples exposed in each unit. The large differences in degradation rate between the individual units is readily apparent. This type of difference between supposedly identical units operating under supposedly identical test conditions can affect decisions regarding material acceptability. For example, if a specification stated that this type of sheeting had to have a minimum of 50 percent retained brightness after 1,500 hr, results from three of the units could be used to reject the material whereas results from the other three units would support material acceptance.

Similar results are shown in Figure 6 for exposures of identical samples of retroreflective sheeting lot D in four fluorescent UV/condensation devices operated per ASTM Standard Practice G53-84. Again, each data point represents mean retroreflectivity retention for three replicates exposed in each machine. All units used FS-40 UVB fluorescent lamps and were operated using a cycle of 4 hr UV at 60°C and 4 hr condensing moisture at 50°C. If a specification required 80 percent brightness retention after 2,200 hr exposure, results from Unit 3 would be sufficient for rejection, those from Units 2 and 4 would be considered marginally acceptable, and those from Unit 1 would easily pass the requirement.

The data in Figures 5 and 6 indicate the high degree of variability in artificial accelerated exposure testing. Clearly, 1,000 hr in one unit is not the same as 1,000 hr in another even when both are operating to the same conditions described in a specified test method. The inherent variability associated with artificial accelerated exposure testing means that use of specifications mandating a specified performance level after a specific exposure period can lead to decisions on product acceptability based on test variability rather than product performance.

Prediction of Sheeting Performance

Instead of using absolute measures of performance, several authors have advocated ranking the performance of a series

TABLE 3 RETROREFLECTIVE SHEETING SERIES 1—FLORIDA 45-DEGREE EXPOSURES: EFFECT OF EXPOSURE PERIOD ON RESULTS

Exposure Period	Total Time Exposed	% Retained Retroreflectivity for the Nine Lots in the Series: Mean	Standard Deviation
12/81 to 12/82	12 months[1]	27.9%	7.1%
4/84 to 4/85	12 months	96.0%	2.1%
6/85 to 6/86	24 months	64.6%	11.1%

[1] Samples retired

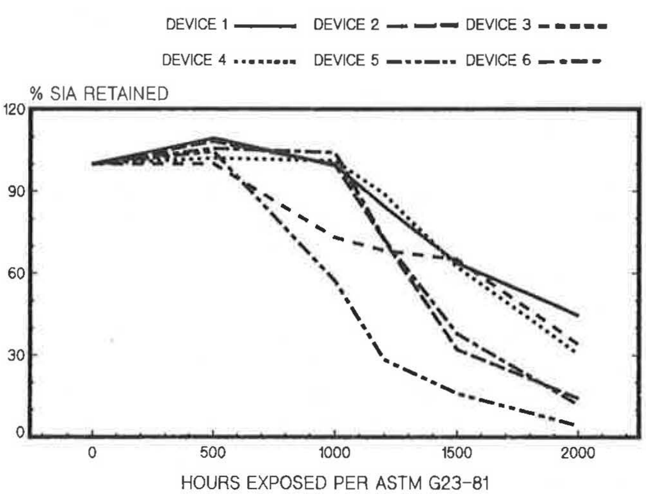

FIGURE 5 Results for identical samples of retroreflective sheeting lot C exposed in six Atlas Model XW Sunshine Carbon Arc Weatherometers all operated per ASTM G23-84, Type E, Method 1.

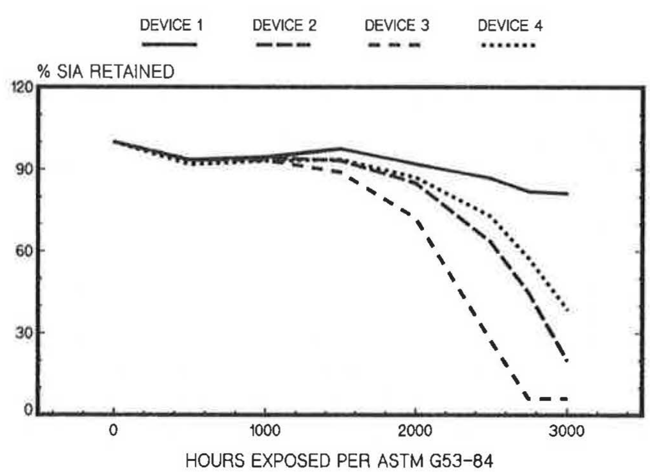

FIGURE 6 Results for identical samples of retroreflective sheeting lot D exposed in four fluorescent UV/condensation devices operating using an identical cycle per ASTM G53-84.

TABLE 4 PERCENT RETAINED RETROREFLECTIVITY OF SHEETINGS EXPOSED IN ARTIFICIAL ACCELERATED AND EXTERIOR TESTS

Reflective Sheeting Number	2500 Hour ASTM G23 type E	3000 Hour ASTM G26 type B	2500 Hours ASTM G53-84 UVB Lamp	Five Years F45°	Five Years AZ45°[1]
1	83	79	80	66	79
2	70	75	33	60	84
3	86	78	24	23	41
4	58	82	14	14	76
5	88	84	98	30	94
6	43	61	41	68	67
7	38	62	30	50	59
8	82	72	75	89	77

[1] Samples exposed in Arizona were mounted on racks backed with black painted plywood and those exposed in Florida were on open backed racks.

TABLE 5 CORRELATION COEFFICIENTS (r) FOR RETROREFLECTIVITY RETENTION OF SHEETINGS IN ACCELERATED AND EXTERIOR EXPOSURES

Correlation Pair	r
2500 hr G23 and 5 yr F45	-.05
2500 hr G23 and 5 yr AZ45	.25
3000 hr G26 and 5 yr F45	-.55
3000 hr G26 and 5 yr AZ45	.37
2500 hr G53 and 5 yr F45	.39
2500 hr G53 and 5 yr AZ45	.62

of materials in artificial accelerated tests (*10*). These ranks are then compared with those obtained in exterior exposures. The results for artificial accelerated and exterior exposures of sheeting series 2 are shown in Tables 4–7. This series is made up of eight different retroreflective sheetings of varying type (enclosed lens, encapsulated lens, and cube corner). The artificial accelerated exposures were conducted using the test cycles described in the section on Exposure Experiments. As indicated previously, the Arizona and Florida 45-degree angle exposures were conducted per ASTM G7. Table 4 summarizes the percent retained retroreflectance for each sheeting obtained in the three artificial accelerated tests and in the Arizona and Florida 45-degree angle exposures.

Table 5 shows the results obtained when the retro-reflectivity retentions from the accelerated tests are correlated with those from the Florida or Arizona exposures. The correlation coefficient, r, was calculated according to Equation 1 and is a measure of the degree of association between two sets of data. Values of r range from -1 to 1, with values near 0 indicating no association and absolute values of 0.90 or greater indicating strong association. One can easily see that the correlation of retroreflectivity retention between artificial accelerated exposures and exterior exposures is very poor.

$$r = \frac{\Sigma (x - \bar{x})(y - \bar{y})}{[\Sigma (x - \bar{x})^2 \, \Sigma (y - \bar{y})^2]^{0.5}} \tag{1}$$

The percent retained retroreflectance was then used to rank the performance of the eight sheetings in the artificial accelerated tests and the exterior exposures. These performance rankings are shown in Table 6 and were used to determine rank correlation coefficients, again using Equation 1, which are summarized in Table 7. The correlation coefficients are higher than those obtained for the brightness retentions but are still too low to allow the use of these accelerated tests as any predictor of exterior performance. The validity of rank correlations depends on sample size, but it is generally accepted that rank correlation coefficients of 0.90 or greater are necessary for highly predictive results (*11*). Note the poor rank correlation between the Florida and Arizona exposures. This is a clear indication that performance in one location cannot

TABLE 6 RETROREFLECTIVE SHEETING PERFORMANCE RANKING IN ARTIFICIAL ACCELERATED AND EXTERIOR EXPOSURES

Reflective Sheeting Number	2500 Hour ASTM G23 type E	3000 Hour ASTM G26 type B	2500 Hours ASTM G53-84 UVB Lamp	Five Years F45°	Five Years AZ45°
1	6	6	7	6	6
2	4	4	4	5	7
3	7	5	2	2	1
4	3	7	1	1	4
5	8	8	8	3	8
6	2	1	5	7	3
7	1	2	3	4	2
8	5	3	6	8	5

NOTE: In this ranking, 1 is poorest, 8 is best.

TABLE 7 RANK CORRELATION COEFFICIENTS (r) BETWEEN ARTIFICIAL ACCELERATED AND EXTERIOR EXPOSURES OF RETROREFLECTIVE SHEETINGS

Correlation Pair	r
2500 hr G23 and 5 yr F45	-.17
2500 hr G23 and 5 yr AZ45	.43
3000 hr G26 and 5 yr F45	-.62
3000 hr G26 and 5 yr AZ45	.50
2500 hr G53 and 5 yr F45	.57
2500 hr G53 and 5 yr AZ45	.69
5 yr F45 and 5 yr AZ45	.19

necessarily be used to predict how a product will perform in another environment.

Use of Artificial Accelerated Testing

Artificial accelerated testing can still serve as one of the many tools used to test retroreflective sheetings. However, the significant variability inherent in these tests must be taken into account. Replicate samples (for example, Federal Specification LS300-C requires exposure of three replicates) of each lot being tested must be used. Use of multiple replicates allows evaluation of results by using statistical techniques of such as analysis of variance. However, a control lot or reference material must be exposed with each series being tested to compensate for the variability inherent in the test. The control should be a material of known performance in artificial accelerated and exterior exposures. This is especially important if one is attempting to compare exposures between different units of the same type or between exterior exposure periods. If these precautions are taken, artificial accelerated testing can be used to help assess the durability of materials having similar composition and construction.

The large variability in artificial accelerated tests coupled with the year-to-year differences in climate at a single exterior exposure site make development of "acceleration factors" used to extrapolate exterior performance from artificial accelerated results a meaningless exercise. Comparing performance within a series using rank correlation techniques (*11*) is a promising approach to evaluating exposure data and may assist in the development of artificial accelerated test cycles that will some day provide more realistic assessment of durability.

Obtaining Accelerated Exposure Results for Retroreflective Sheetings

The results described in previous sections show that standard or commonly used artificial accelerated exposure tests are not satisfactory for predicting long-term exterior durability for retroreflective sheetings. However, one is still left with the problem of obtaining reliable indications of long-term durability in a shortened time frame. The use of outdoor exposures at a 45-degree angle facing the equator is a commonly used practice for obtaining "accelerated" outdoor exposures and probably stems from early work in temperate latitudes where 45-degree exposures are the optimum angle to maximize total UV stresses. Zerlaut (*12*) has shown that samples exposed horizontally in humid southern climates receive 10 percent more solar radiation than those at 45 degrees. However, experiments evaluating alternate exposure angles have shown no significant increases in failure rates relative to those seen in 45-degree exposures (*13*).

Materials exposed at 45-degree angles receive significantly higher levels of each of the primary stresses that produce polymer degradation (UV, moisture, and temperature) than those exposed vertically. Results from solar UV measurements (*14*) between 300 and 400 nm for a south-facing 45-degree angle and vertical exposures are shown in Table 8. One can see that samples exposed at a 45-degree angle receive 50 percent more solar UV annually and 74 percent more during the warmer summer months than those exposed vertically.

Table 9 summarizes results (*1*) from time of wetness measurements made on samples exposed vertically and at a 45-degree angle. Over a 12-month exposure, samples at 45 degrees are wet 47 percent longer than those exposed vertically. During the summer months (April–September), a 45 degree orientation increases wet time by 32 percent. In addition, there are many more wet and dry cycles that could produce mechanical stresses due to expansion and contraction as polymers swell with absorbed moisture and then shrink as moisture evaporates.

There is little published research comparing temperatures between angled and vertical exposures. For 3 weeks during April–May 1986, black panel temperatures for vertical and 34 degrees (latitude angle) were continuously monitored in Phoenix, Arizona. Table 10 summarizes the results for several times and shows that during midday, the 34-degree angle black panel temperature is typically 12°C higher than that for the vertical orientation. It is recognized that this temperature difference will double the rate of many chemical reactions, including those involved in polymer degradation. Long-term studies comparing temperatures of retroreflective sheetings at 45-degree angles and vertical exposures are now under way in several locations.

The results presented in Tables 8–10 illustrate how 45-degree angle exposures increase the stresses producing polymer degradation but do not provide an indication of the increase in failure rates for materials exposed at 45 degrees. In order to estimate the effect of exposure orientation on failure rates for retroreflective sheetings, multiple samples of a model sheeting based on an aminoplast cross-linked polyester polymer were exposed during 1986–1987 in Phoenix and Miami. Twelve samples were prepared for each exposure condition and one sample was recalled each month for testing. From plots of property versus exposure time, failure times were determined for retroreflectance loss, gloss loss, and yellowing. Failure time was defined as the time to 50 percent loss of retroreflectivity or 60-degree gloss, or time to maximum yellowing as measured by ASTM D1925 Yellowness Index. Table 11 summarizes failure times for each property in each exposure orientation.

The acceleration achieved by 45-degree exposures is generally near 2:1 but depends somewhat on the property being monitored. This agrees with the work of Yamasaki and Blaga (*15*), who reported that 45-degree exposures produced a 2:1 acceleration in loss of tensile impact strength for polyvinyl chloride relative to vertical exposures. Note that solar tracking exposures did not produce faster retroreflectivity loss or yellowing relative to static 45-degree exposures for this model sheeting. The only increase in failure rate for the solar tracking exposures was for gloss loss in Arizona.

TABLE 8 SOLAR UV FOR 45-DEGREE AND 90-DEGREE SOLAR EXPOSURES (*14*)

Time Interval	MJ/m^2 Solar UV (300-400nm) 90^o	45^o
12 months	131	197
summer (Apr-Sept)	76.5	133

TABLE 9 TIME OR WETNESS FOR 45- AND 90-DEGREE SOLAR EXPOSURES (*2*)

	90^o			45^o		
Time Interval	Wet Time (hours)	% of Total	# of wet/dry cycles	Wet Time (hours)	% of Total	# of wet/dry cycles
12 months	1875	21.3%	345	2753	31.3%	407
summer (Apr-Sept)	913	26.2%	188	1204	37.8%	240

TABLE 10 BLACK PANEL TEMPERATURES AT 34 AND 90 DEGREES

Time	Orientation	Mean Temp (°C)	Standard Deviation	F-Ratio for ANOVA[1]
8AM	air temp	20.6	4.7	21.96
	90°	24.8	4.8	
	34°	30.3	6.3	
10AM	air temp	24.6	4.8	81.98
	90°	33.1	4.6	
	34°	44.5	7.0	
Noon	air temp	27.5	4.5	152.80
	90°	39.5	4.6	
	34°	51.9	5.9	
2PM	air temp	29.3	4.5	124.85
	90°	39.7	4.3	
	34°	51.9	6.1	
4PM	air temp	29.1	5.1	30.41
	90°	34.6	6.0	
	34°	43.1	8.0	

[1] For this analysis, to be 99% confident that the means are significantly different, the critical F ratio is 8.0166.

CONCLUSIONS

Artificial accelerated exposure tests are inadequate for assessing durability of retroreflective sheetings because they are poor replications of exterior exposure conditions and produce highly variable results for identical samples exposed in equivalent devices. Performance rankings of retroreflective sheetings exposed in standard artificial accelerated tests correlate poorly with those obtained in exterior tests. Accelerated indications of retroreflective sheeting durability can be obtained using 45-degree exterior exposures. These exposures produce higher levels of solar UV, moisture, and temperature than those in a vertical orientation and typically accelerate failures by a factor of 2:1. Surprisingly, solar tracking exposures produced little increase in failure rate relative to static 45-degree exposures. Performance of sheetings in one location is not necessarily a good predictor of performance in another environment. Therefore, exterior exposure testing at sites representative of end use applications are necessary. Multiyear exposures are recommended to minimize seasonal and year-to-year effects that contribute to variability of results.

In order to obtain reliable results, exposure testing should always use several replicates of each material being tested and must include a control of known performance as a reference.

ACKNOWLEDGEMENTS

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TABLE 11 FAILURE RATES FOR MODEL RETROREFLECTIVITY SHEETING AS A FUNCTION OF EXPOSURE ORIENTATION

Exposure	Property	Time to Failure[1]	Acceleration Relative to 90° Exposure
Arizona 90°	COR[2]	6 months	
Arizona 45°		3 months	2:1
AZ solar track[3]		3 months	2:1
Arizona 90°	60° Gloss	9 months	
Arizona 45°		3 months	3:1
AZ solar track		2 months	4.5:1
Arizona 90°	Yellowing	8 months	
Arizona 45°		5 months	1.6:1
AZ solar track		5 months	1.6:1
Florida 90°	COR	9 months	
Florida 45°		4 months	2.2:1
FL solar track		4 months	2.2:1
Florida 90°	60° Gloss	10.5 months	
Florida 45°		6 months	1.8:1
FL solar track		6 months	1.8:1
Florida 90°	Yellowing	10 months	
Flordia 45°		6 months	1.7:1
FL solar track		6 months	1.7:1

[1] Failure is defined as 50% drop in coefficient of retroreflection, 50% gloss loss, or time to maximum yellowness index

[2] COR = coefficient of retroreflection

[3] East-west solar tracking, latitude angle (26° in Florida, 34° in Arizona) exposures

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