Prediction of Mechanical Properties of Weather-Induced Degraded Plastics in Saudi Arabia

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SYNOPSIS

Empirical equations have been developed to predict the mechanical properties of greenhouse films when exposed to natural weather conditions for long durations. Tensile strength and percent elongation data obtained for the Dhahran site was used to develop empirical equations. Prediction models were developed with exposure time as independent parameter for both tensile strength and percent elongation, which were taken as dependent parameter. The mean deviations for tensile strength and percent elongation were found to be 2.5 and 1.2%, respectively. Weather data of Dhahran for the period of natural exposure is also presented. © 1995 John Wiley & Sons, Inc.

INTRODUCTION

The utilization of plastics in outdoor applications has grown rapidly with the overall development of Saudi Arabia. One of the major problems faced by the plastic products used outdoor is weather-induced degradation. The various weather parameters which may contribute in the degradation of plastics are solar radiation, temperature, humidity, wind, rain, environmental pollutants, sand abrasion, and thermal cycling (cold night and hot days). The extent of plastic degradation can be evaluated by measuring the various properties after prolonged exposure to the harsh weather conditions at various representative locations.[1]

The ability to predict critical properties of weather-induced degraded plastics is of great importance. It helps in determining the useful life (durability) of the plastic products for better planning in maintenance and replacement. Mechanical properties (tensile strength and percent elongation) data were generated for the five sites, namely, Baha, Dhahran, Jeddah, Riyadh, and Tabuk. The Dhahran data were used to develop empirical models to predict mechanical properties.

Weather Conditions

The deterioration of a material depends on how and to what extent it interacts with its surroundings. Heat, radiation, rain, humidity, atmospheric contaminants, thermal cycling, and oxygen content of air all contribute to the degradation of plastics subjected to outdoor exposure.

Dhahran is located in the eastern part of Saudi Arabia (26.32°N, 50.13°E). The total solar radiation received at Dhahran during the test period is shown in Figure 1. Variation in ambient temperature and relative humidity are illustrated in Figures 2 and 3, respectively.

The most deleterious of the environmental factors in the weathering phenomena is the ultraviolet (UV) section of radiation, which is responsible for the weather-induced degradation of plastics.[2-4] The high levels of temperature, humidity, and solar radiation found in tropical regions such as Dhahran proved to be more aggressive to plastic materials than temperate zones.[5]

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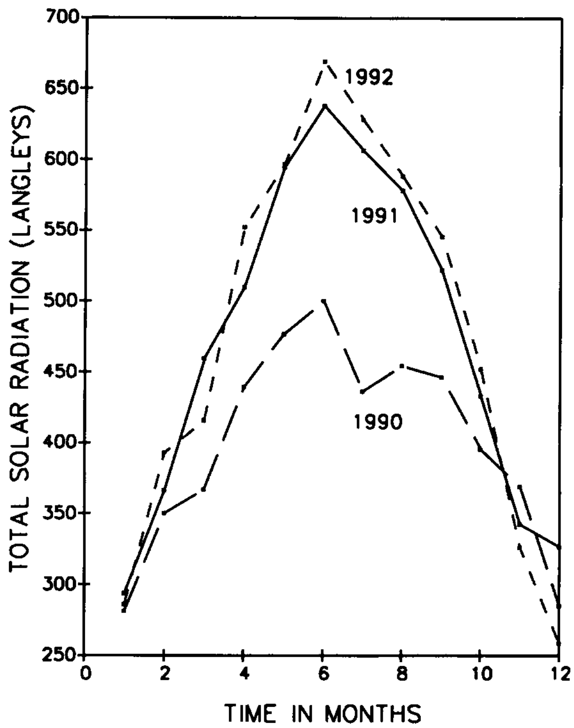

Figure 1 Variation in total solar radiation with time at Dhahran.

EXPERIMENTAL

A 5-kilonewton (kN) Instron Model 4301 Universal testing machine was used to determine the tensile properties of polymeric material. The full-scale load range (using interchangeable 2518-load cells) is 0.5 N to 5 kN. The crosshead speed range is 0.5–500 mm/min and 100 mm/min was used for this work. The crosshead speed accuracy is ±0.5% over 100 mm (no load) and ±0.75% over 100 mm (max. load). The test specimens were prepared according to the recommendations made in ASTM standard D-638M-84, and the test was also conducted using the same standard. Test conditions were maintained according to the standard laboratory atmosphere of 23 ± 2°C and 50 ± 5% relative humidity. Ten replicates of each samples were tested to get one value, and the reproducibility and repeatability of the test was maintained according to the ASTM standard D-638M-84.

Polyethylene-based greenhouse film was used in this study. The UV stabilizer incorporated in the film formulation was Ciba-Geigy-based Hindered Amine Light Stabilizer (HALS). The 200-μm-thick film was produced using low-density polyethylene

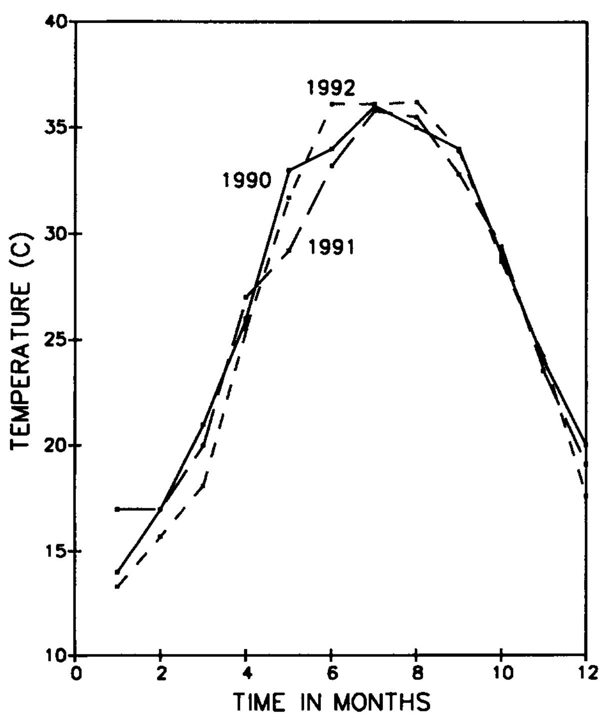

Figure 2 Variation in ambient temperature with time at Dhahran.

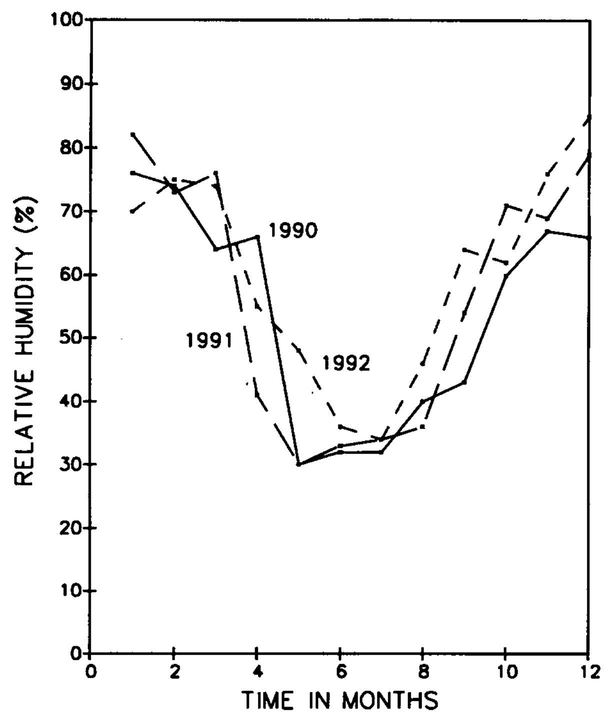

Figure 3 Variation in relative humidity with time at Dhahran.

Table I Specifications of Greenhouse Film Used in the Study

General Properties	Value	Unit	Test Method
Polymer			
Melt index IF (190 A5C)	0.24–0.30	g	NF T 51-016
Density (23°C)	0.921–0.923	g/cm^3	ASTM D-2839
Crystalline melting point	115	°C	ASTM D-2117 NF T 51-621
Vicat softening point	97	°C	NF T 51-021[a] (Method A)
Elastic limit	11	N/mm^2 [b]	NF T 51-034
Tensile strength	20	N/mm^2 [b]	(100 mm/mn)[a]
Elongation at break	650	%	
Flexural modulus	290	N/mm^2 [b]	ASTM D-790[a]
Upper calorific value	10,900	cal/g	Calorimeter
Oxygen	17.5	%	ASTM D-2863 NF T 51-071
Film[c]			
Tensile strength, $L + T/2$	22	N/mm^2 [b]	ASTM D 882 (500 mm/mn)
Elongation at break	800	%	NF T 54-102
Tear resistance	1200	g	ASTM D-1922
Impact resistance	600	g	NF T 54-109

[a] Using a compression molded sample. Annealed at 100°C (CdF laboratory method).
[b] 1 N/mm^2 = 10.2 kg/cm^2
[c] Using film 200 μm thick and extruded with a blow ratio of 2.

(LDPE) Lotrene FB3003 obtained from Qatar Petrochemical Company (QAPCO). The specifications of Lotrene FB 3003 are given in Table I.

MODEL DEVELOPMENT

Models of any type, regardless of their sophistication and accuracy in representing the real system, may prove to be of little value if they are not supported by reliable data. In this study, Statistical Analysis System (SAS) software package was used to estimate the unknown coefficients in the regression model.[6] Regression analysis is a statistical technique for modeling and investigating the relationship between the dependent and independent variables. This study presents the models developed based on Dhahran data.

One of the criteria in the development of the empirical equations in this study is to formulate a simple user-friendly relationship with reasonable accuracy. The mechanical properties (tensile strength, percent elongation) of plastic materials were taken as dependent variables, and exposure time was taken as independent variable. Exposure time as independent variable will account for the cumulative effect of all weather parameters. It is also simple to use because the user needs only elapsed time as an input. Tensile strength and percent elongation data obtained for 3 years for the greenhouse film was analyzed and used for the development of the models.

A search of the literature indicated that there are

Table II Results of Regression Analysis Using Existing Empirical Models Available in the Literature

Relationship	Mean Dev. (%)	Max. Dev. (%)	Reference No.
$y = A \exp[B(t - c]$	SAS failed to converge	—	7
$y = K - A \exp(-Bt^2)$	14.6	28.0	8
$y = C + A \exp(-Bt^n)$	14.6	28.0	9

Table III Results of Regression Analysis Using Different Relationships Proposed for Tensile Strength in this Study for Dhahran Site

S. No.	Relationship	Mean Dev. (%)	Max. Dev. (%)
1	$T_s = C_0 + C_1(T_M) + C_2(T_M)C_3$	2.5	8.1
2	$T_s = C_0 + C_1(T_M) + C_2(T_M)^2$	2.5	8.7
3	$T_s = C_0 + C_1(T_M)^{1/2} + C_2(T_M)^2$	2.8	9.3
4	$T_s = C_0 \exp(-C_1\,(T_M)^2 + C_2(T_M)$	41.7	92.9

Table IV Experimental and Predicted Tensile Strength of Greenhouse Film at Dhahran Using Proposed Empirical Model

Month	TS Exp.	TS Calc.	% Deviation
0	23.880	23.880	0
2	22.990	23.581	2.569
4	23.120	23.279	0.686
6	25.160	22.974	−8.689
8	22.880	22.667	−0.933
10	22.620	22.356	−1.165
12	22.560	22.044	−2.288
14	22.460	21.728	−3.258
16	22.300	21.410	−3.990
18	19.940	21.089	5.765
20	19.870	20.766	4.509
22	19.670	20.440	3.914
24	19.570	20.111	2.106
26	19.540	19.780	1.226
28	19.500	19.445	−0.280
30	19.020	19.108	0.465
32	18.790	18.769	−0.112
34	18.720	18.427	−1.567
36	18.650	18.082	−3.046

few models available to predict mechanical properties of plastic materials. Before initiating the work on the model development, an attempt was made to investigate the applicability of the existing models available in the literature. Some of the models found in the literature are listed in Table I and were used in the regression model to predict tensile strength of greenhouse film exposed in Dhahran. The mean and maximum deviations obtained are shown in Table II.

Many relationships were proposed and studied by the investigators to predict the tensile strength of the greenhouse film. Some of the equations which gave reasonably good results for Dhahran are listed in Table III.

After investigating several models, including those listed in Table II, the following relationship was finally selected:

$$T_S = C_0 + C_1(T_M) + C_2(T_M)^2 \quad (1)$$

where T_S is tensile strength (MPa), T_M is time in months, C_0 is 23.88 (tensile strength of virgin sample at $T_M = 0$), and C_1, C_2 are constants.

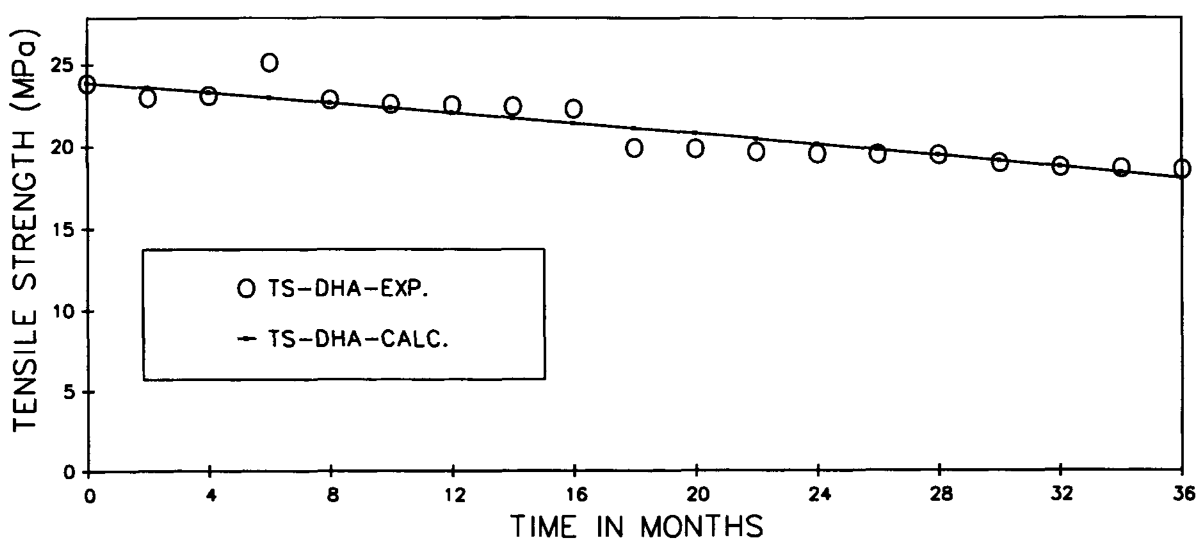

Figure 4 Experimental data and predicted values of tensile strength as a function of exposure time at Dhahran.

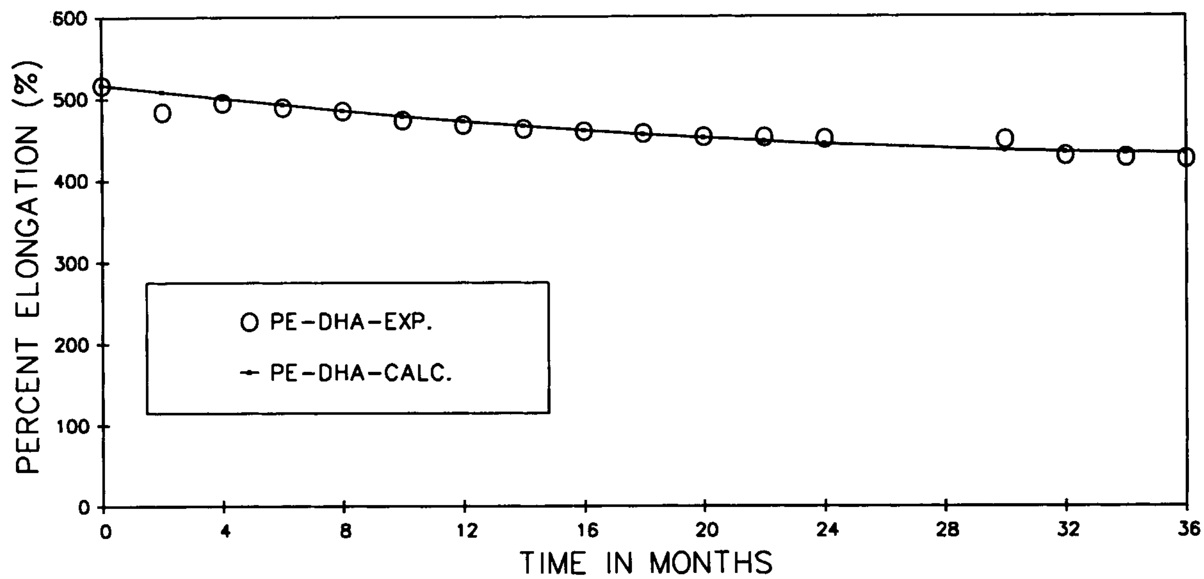

Figure 5 Experimental data and predicted values of percent elongation as a function of exposure time at Dhahran.

The first equation in Table III gave the lowest maximum deviation, but the second equation was selected because of simplicity and very little difference in their maximum deviations.

Tensile Strength Prediction Model

The value of the constant C_0 was taken as 23.88, which is the tensile strength of the virgin sample at time zero. The empirical model proposed for the Dhahran site to predict the tensile strength of greenhouse film is as follows:

$$T_S = 23.88 - 0.149(T_M) - 0.000329(T_M)^2 \quad (2)$$

Table IV shows the experimental and predicted values of tensile strength, and Figure 4 shows the comparison between the experimental and the predicted values. The maximum deviation of 8.7% occurred at month 6 probably due to crosslinking, and the deviations were relatively low toward the end of the test period. The mean deviation was 2.5% and maximum deviation was 8.7% with coefficient of determination R^2 as 0.86.

Percent Elongation Prediction Models

The functional form used for the tensile strength prediction was adequate for the percent elongation prediction also. The mean and maximum deviations and R^2 values were found to be acceptable for engineering purposes. The function used was a second-order equation which has three coefficients C_0, C_1, and C_2 and has the following form:

$$PE = C_0 + C_1(T_M) + C_2(T_M)^2 \quad (3)$$

Table V Experimental and Predicted Elongation of Greenhouse Film at Dhahran Using Proposed Empirical Model

Month	PE Exp.	PE Calc.	% Deviation
0	517.500	517.500	0.000
2	484.000	508.854	5.135
4	495.500	500.670	1.043
6	490.000	492.946	0.601
8	485.400	485.682	0.058
10	474.200	478.880	0.987
12	468.500	472.538	0.862
14	463.400	466.658	0.703
16	460.500	461.238	0.160
18	458.200	456.278	−0.419
20	454.000	451.780	−0.489
22	453.000	447.742	−1.161
24	451.000	444.166	−1.515
30	450.000	436.200	−3.067
32	430.500	434.466	0.921
34	428.000	433.194	1.213
36	426.000	432.382	1.498

Table VI Coefficients of the Models for the Prediction of Tensile Strength and Percent Elongation

Property	C_0	C_1	C_2	Mean.	Max.	R^2
Tensile strength	23.880	−0.149	−0.000335	2.48	8.68	0.859
Percent elongation	517.5	−4.438	0.0576	1.16	5.13	0.894

where PE is percent elongation (predicted), T_M is time in months, and C_0, C_1, and C_2 are regression coefficients.

The value of C_0 was fixed at 517.5 which is the percent elongation of the virgin sample at time zero. The coefficients C_2 and C_3 were determined using SAS.

The proposed model for the prediction of percent elongation of greenhouse film at Dhahran is as follows:

$$PE = 517.5 - 4.438(T_M) + 0.0576(T_M)^2 \quad (4)$$

The mean and maximum deviations were 1.2 and 5.1%, respectively. The coefficient of determination R^2 was 0.89. Figure 5 shows the comparison between the experimental and the predicted values of percent elongation, and Table V lists the experimental data and predicted values for the Dhahran site.

Summary of Models

The relationships which are adequate for predicting both tensile strength and percent elongation of greenhouse film exposed to outdoor weather conditions are as follows:

$$TS \quad \text{or} \quad PE = C_0 + C_1(T_M) + C_2(T_M)^2 \quad (5)$$

where TS is tensile strength (MPa), PE is percent elongation, C_0 is initial value of tensile strength or percent elongation, and C_1, C_2 are regression coefficients.

The value of C_0 was fixed at initial conditions. In case of tensile strength, it is 23.88 and in case of percent elongation it is 517.5. Table VI summarizes the values of coefficients C_0, C_1, and C_2 to be used in Eq. (5) to predict the tensile strength and percent elongation of greenhouse film for the Dhahran site in Saudi Arabia. The mean deviations range between 1.2 and 2.5% with a maximum deviation up to 8.1%. The coefficient of determination (R^2) in each case is very good and within the limits for engineering purposes.

In general, the models are accurate for the prediction of mechanical properties of greenhouse film for the Dhahran site. These models may be utilized for locations having similar weather conditions as that of Dhahran.

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