Stress Relaxation Behavior of HDPE Geomembranes

T. -Y. Soong, A. E. Lord, Jr. & R. M. Koerner
GRI/Drexel University, Philadelphia, PA, USA

ABSTRACT: In order to evaluate the time dependent behavior of a commercially available 1.5 mm HDPE geomembrane, a systematic set of stress relaxation laboratory tests was performed. After initial stress and strain controlled attempts at reaching a targeted value to begin the tests were concluded, an optimum test protocol was established. Subsequent tests were performed at –10, 10, 30, 50 and 70°C. Results indicate a high sensitivity to both test procedure and test temperature. Results also show that time-temperature shifting is possible and that viscoelastic concepts should apply. This should enable the results to be compared and contrasted to sustained load creep test results which represent the comparison type of long term stress-related polymer behavior.

1 INTRODUCTION

Whenever stresses are imposed on a geomembrane (via tension, shear, torsion, bending, compression, etc.), they must somehow be internally sustained by its molecular structure. If the stresses are maintained over a sufficiently long period of time, the molecular structure will attempt to accommodate them via creep, stress relaxation or some combination of both. Creep will occur under conditions of increasing deformation with constant stress, while stress relaxation will occur under constrained strain conditions. Applications where these mechanisms might occur are the following:

- side slope cover soils placed on anchored geomembranes
- solid waste landfills placed on sloped geomembranes
- out-of-plane deformation of geomembranes in landfill closures
- out-of-plane deformation of reservoir liners due to uplifting gases
- out-of-plane deformation of landfill covers due to uplifting gases
- canal liners placed over rock, or uneven, subgrades
- construction placed waves (or wrinkles) in geomembranes which are subsequently backfilled

Since many of these applications are a combination of creep and/or stress relaxation, and the creep data base is slightly more advanced than the stress relaxation data base, this paper focuses completely on stress relaxation. As will be noted, however, the two mechanisms are interrelated.

This paper presents stress relaxation data on high density polyethylene (HDPE) geomembranes since they are semi-crystalline (about 60% crystalline and 40% amorphous) and are used widely in the previously listed applications. The particular type of HDPE geomembrane evaluated is 1.5 mm thick and was produced by the flat cast extrusion method. Obviously, other geomembranes could be evaluated in a similar manner and it is hoped that this paper will give insight into the phenomenon and also provide a stimulus to others to enter into this type of testing and evaluation.

2 PAST RESEARCH

In a recent paper (Koerner, et al., 1993), the time-dependent mechanical properties of geosynthetic materials were described. The status of creep and stress relaxation in geotextiles, geogrids and geomembranes was reviewed. For example, Krupin, et al., 1982, present some data on stress relaxation in polyvinyl chloride and polyethylene geomembranes. Greenwood (1990) performed stress relaxation work in HDPE geogrids. Findley (1987) evaluated 26-year duration experimental creep data on thick sections of polyvinyl chloride and polyethylene. There is also related tension creep work in geogrids (Andrawes, et al., 1986, Greenwood, 1990 and Wrigley, 1987).

In house stress relaxation work on geomembranes (Koerner, et al. 1993), shows that stress relaxation in many cases obeys a curve of the form:

$$\sigma(t) = c\, t^{-b} \tag{1}$$

where $\sigma(t)$ is the stress level at time "t", and c and b are constants. This type of behavior has been called "physical stress relaxation" by Debnath (1985). The current study is meant to extend these previous efforts via a systematic evaluation of a commercially available geomembrane product.

3 DETAILS OF THIS STUDY

The stress relaxation tests described in this paper were conducted using an Instron universal testing machine (Model 4206). Loads were measured with a load cell having a rated capacity of 5,000 kN. An environmental chamber (Lab-Temp, Inc.) with temperature controllable to ±1°C, in conjunction with a cryogenic cooling system (liquid carbon dioxide), was used to enclose the test specimen and griping assembly to accommodate both elevated and sub-ambient temperature tests.

The geomembrane used was made from high density polyethylene (HDPE) with a nominal thickness of 1.5 mm. All test specimens were rectangular of 50 mm length and 100 mm width. Note that the test specimens have the same length-to-width ratio as is specified in ASTM D4855 but are 50% of the size due to the necessity of containing the specimen and grips in the environmental chamber.

Two types of initial loading procedures were conducted in this study; stress-controlled and strain-controlled. The experimental design was as follows:

- Initial stress via stress-controlled loading
  - 40% of yield stress @ 10 and 50°C
  - 50% of yield stress @ -10, 10, 30, 50 and 70°C
  - 60% of yield stress @ 50 and 10°C
- Initial strain via strain-controlled loading
  - 1% of strain @ 10 and 50°C
  - 3% of strain @ -10, 10, 30, 50 and 70°C
  - 5% of strain @ 10 and 50°C

Trail tests were performed initially to determine the suitable loading rate. The results suggested a rate of 12.7 mm/min as being appropriate since faster rates caused an "over-shooting" problem, i.e., the cross-head could not be accurately stopped at the desired stress or strain level. At slower rates, a very significant amount of stress relaxation occurred during the loading process. Thus the loading protocol was to ramp up at the test machine strain rate noted above until the desired initial stress or strain level was reached. In all cases, the strain was subsequently held at a constant value during the remainder of the test and stress was monitored over time as is typical of all stress relaxation tests. The tests were conducted for a duration of at least 7,000 min. (5 days) with exceptions being those performed at low temperatures, (i.e., 10 and –10°C) owing to the limitation of cooling agent.

4 RESULTS

Due to the limitation of space, many of the test results cannot be presented in graphic form. However, the importance of those results can not be over-emphasized. Stress relaxation tests started initially at stress levels of 40, 50 and 60% of the yield stress (at the indicated temperature) were performed at temperatures of 10 and 50°C. The results were analyzed by plotting the normalized stress (instantaneous stress/initial stress) against time at each temperature. The curves appeared to follow a unique behavior independent of the initial stress level. In addition, by plotting the time-dependent modulus (instantaneous stress/constant strain) against time, the linearity in the stress-strain relations can also be shown clearly, i.e., the stress relaxation modulus is independent of the initial stress level over this range of stress and strain.

For comparison, stress relaxation tests started initially at strain levels of 1, 3 and 5% were also performed at temperatures of 10 and 50°C. Similar behavior as described with the stress-controlled tests was observed. That is, the normalized stress and the stress relaxation modulus were both seen to be independent of the initial strain level.

Figures 1-3 shows the results of stress relaxation tests started initially at 50% of the yield stress at temperatures of –10, 10, 30, 50 and 70°C. The temperature effects on the time-dependent stress and modulus are shown in Figure 1 and 2, respectively. Temperature effect on the normalized stresses is shown in Figure 3. At face value it appears that the stress relaxes more (after approximately one week of testing) at lower temperatures than at higher temperatures. This assumes that no relaxation occurs during the initial stress application. More research is needed here before a definite statement can be made regarding the final amount of stress relaxation as a function of temperature.

Figures 4-6 present the companion set of test results except the tests were conducted at 3% strain. Again, similar observations can be made as those described with the stress-controlled set of data.

The modulus versus time curves generated at different temperatures can be shifted into a single, continuous curve with respect to a specific reference temperature. This shifting involves both horizontal and vertical displacement of the curves. The generated curve which now covers a much longer time period is called a *master curve*. This well-known technique in polymer viscoelasticity is called *time-temperature superposition*. Figure 7 shows the master curve generated in this study for this particular HDPE geomembrane. The master curve corresponds to the 3% strain data (from Figure 5) at a reference temperature of 10°C and covers a time period up to 11.4 years. It appears from the master curve that a residual modulus value (i.e., stress value) has been reached for the curve becomes horizontal. Information other than the projected time period, such as percent residual modulus (which can be converted back to residual stress) and time to reach 50% relaxation, can also be determined from such master curves. Table 1 summarizes this information for three different reference temperatures (from data of Figure 5) of which the 10°C response is shown in Figure 7.

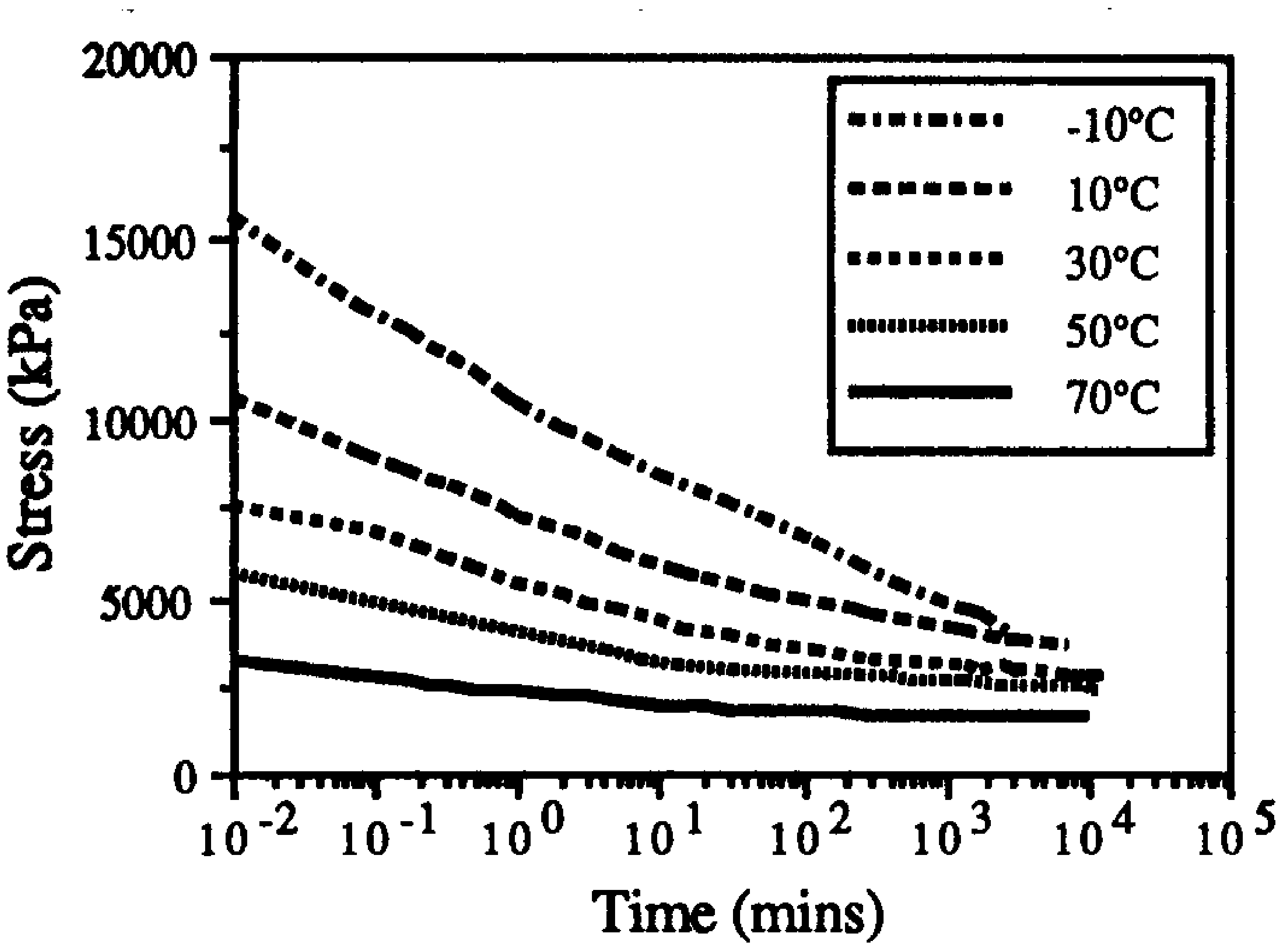

Figure 1 Results of stress relaxation test of 1.5 nm HDPE geomembrane started initially at 50% of yield stress at various temperatutes.

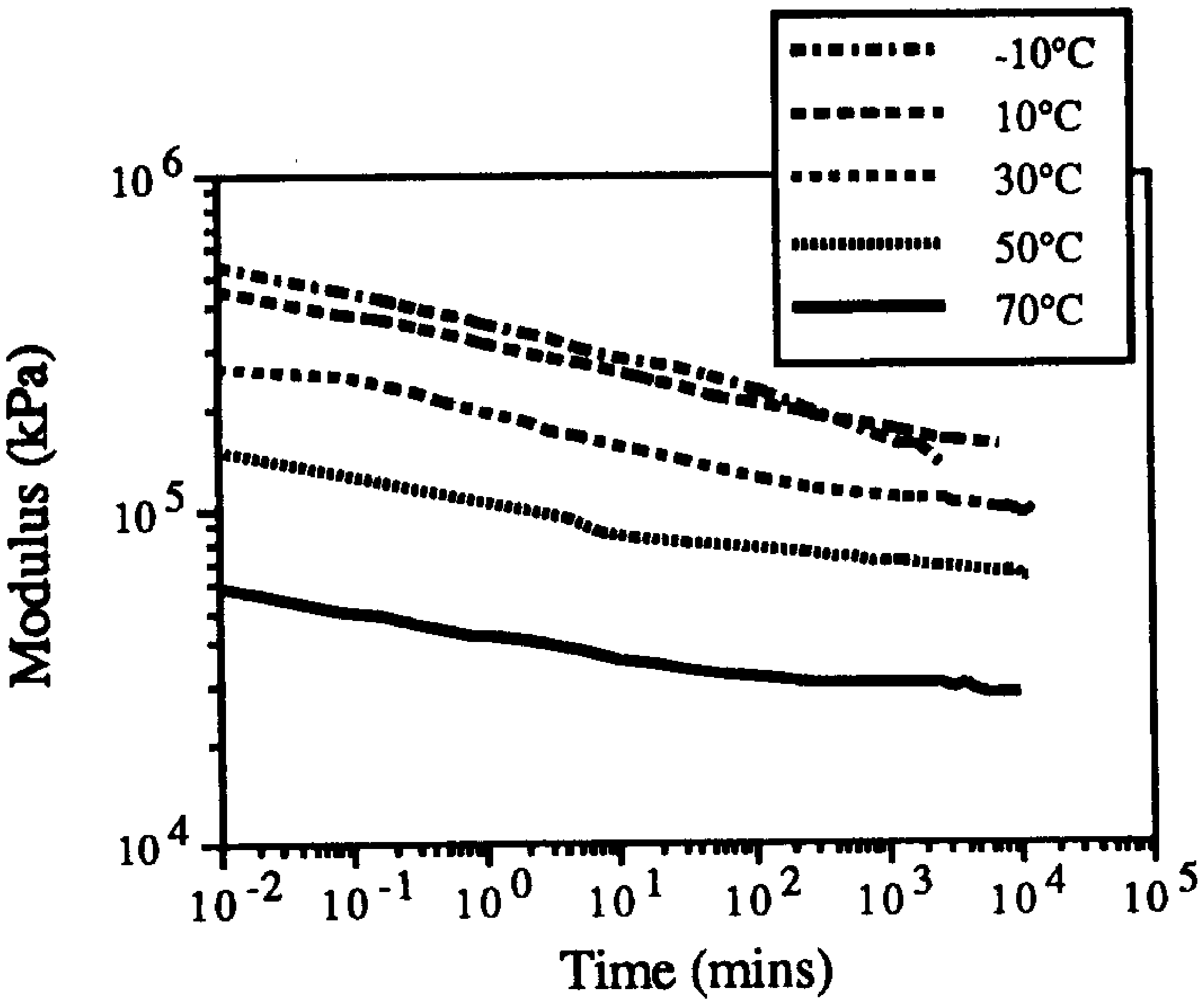

Figure 2 Stress relaxation modulus of 1.5 mm HDPE geomembrane corresponding to initial stress level of 50% of yield stress at various temperatures.

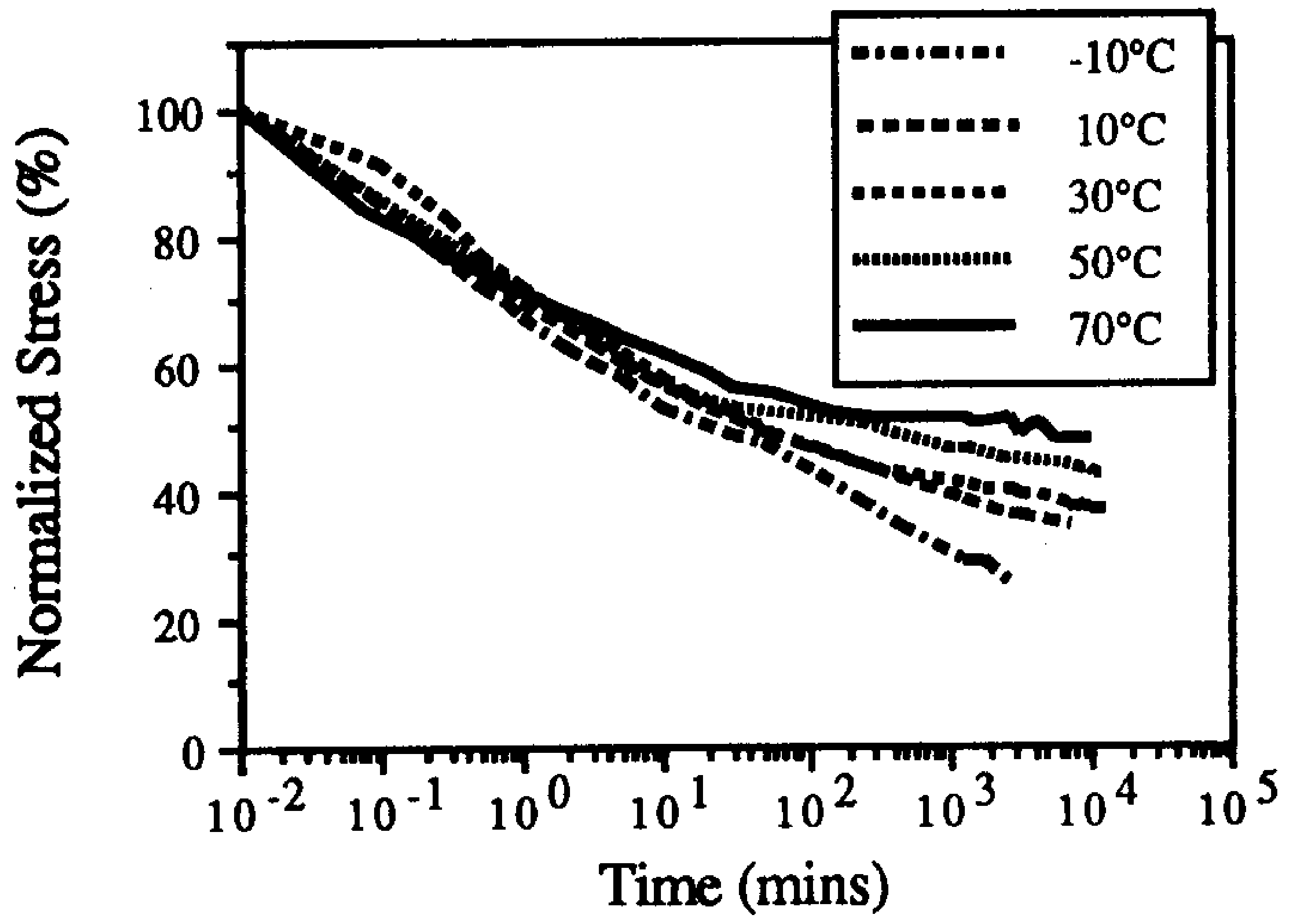

Figure 3 Normalized time-dependent stress of 1.5 mm HDPE geomembrane corresponding to initial stress level of 50% of yield stress at various temperatures.

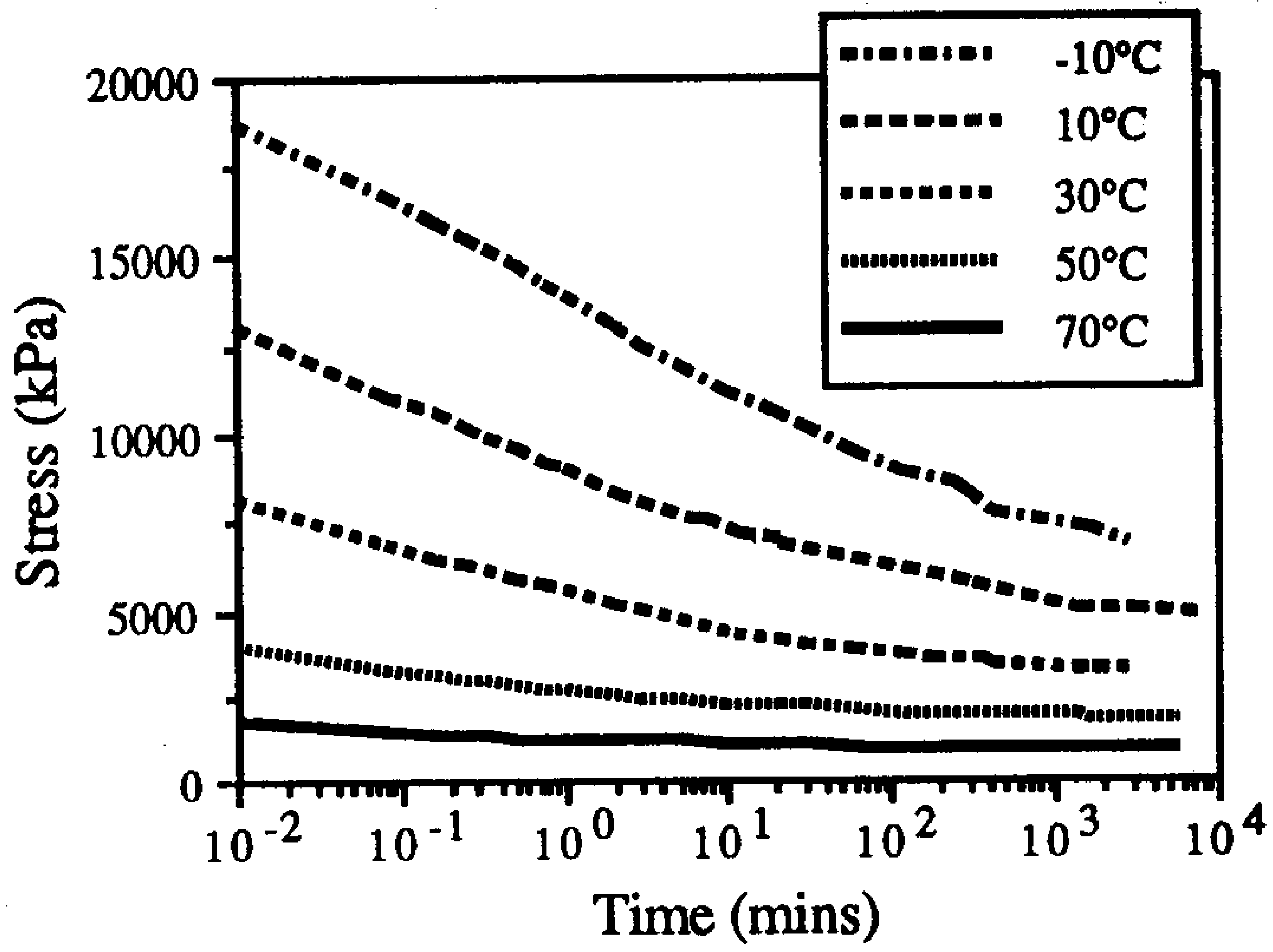

Figure 4 Results of stress relaxation test of 1.5 mm HDPE geomembrane started initially at 3% of strain at various temperatures.

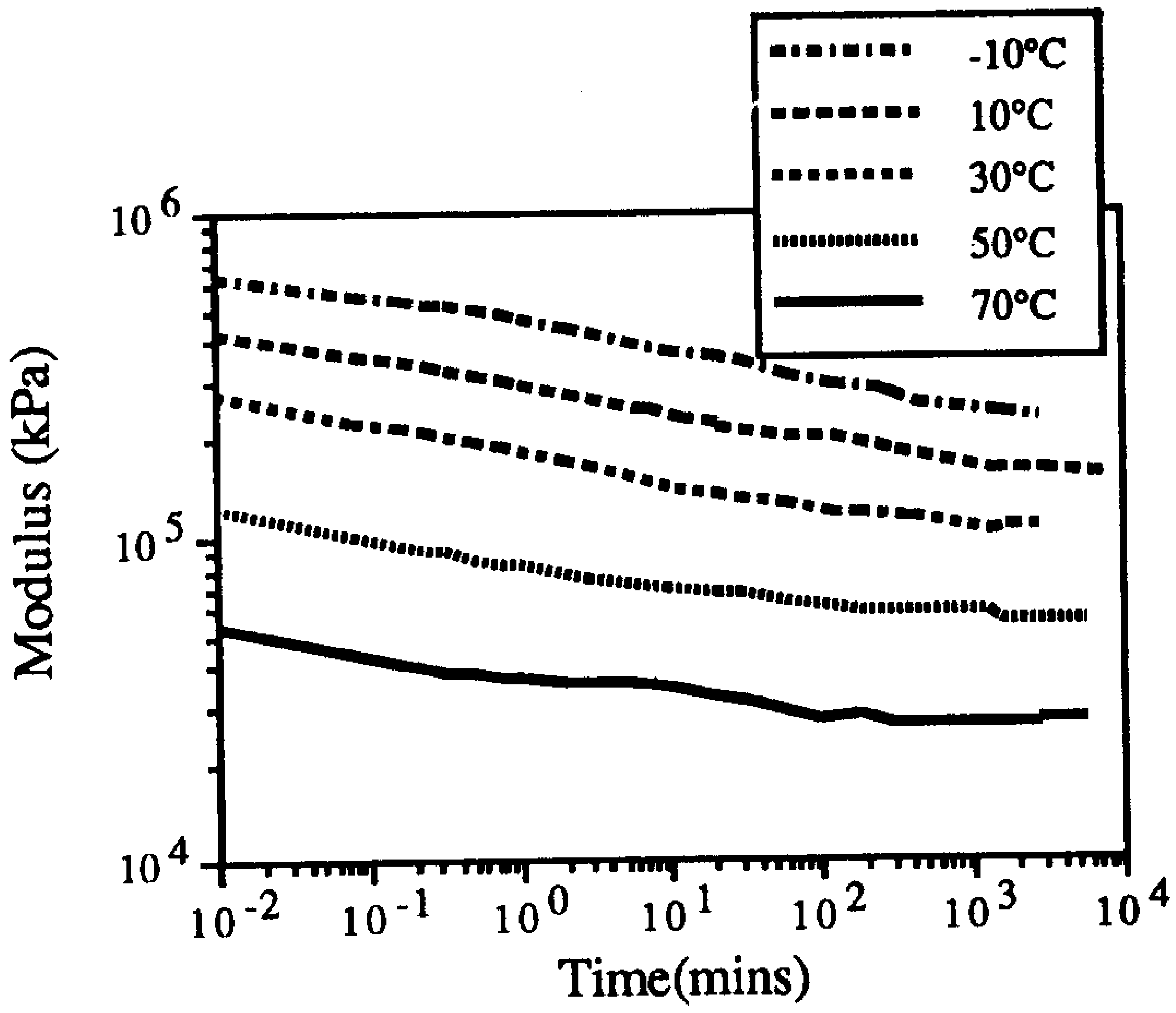

Figure 5 Stress relaxation modulus of 1.5 mm HDPE geomembrane corresponding to initial strain level of 3% of strain at various temperatures.

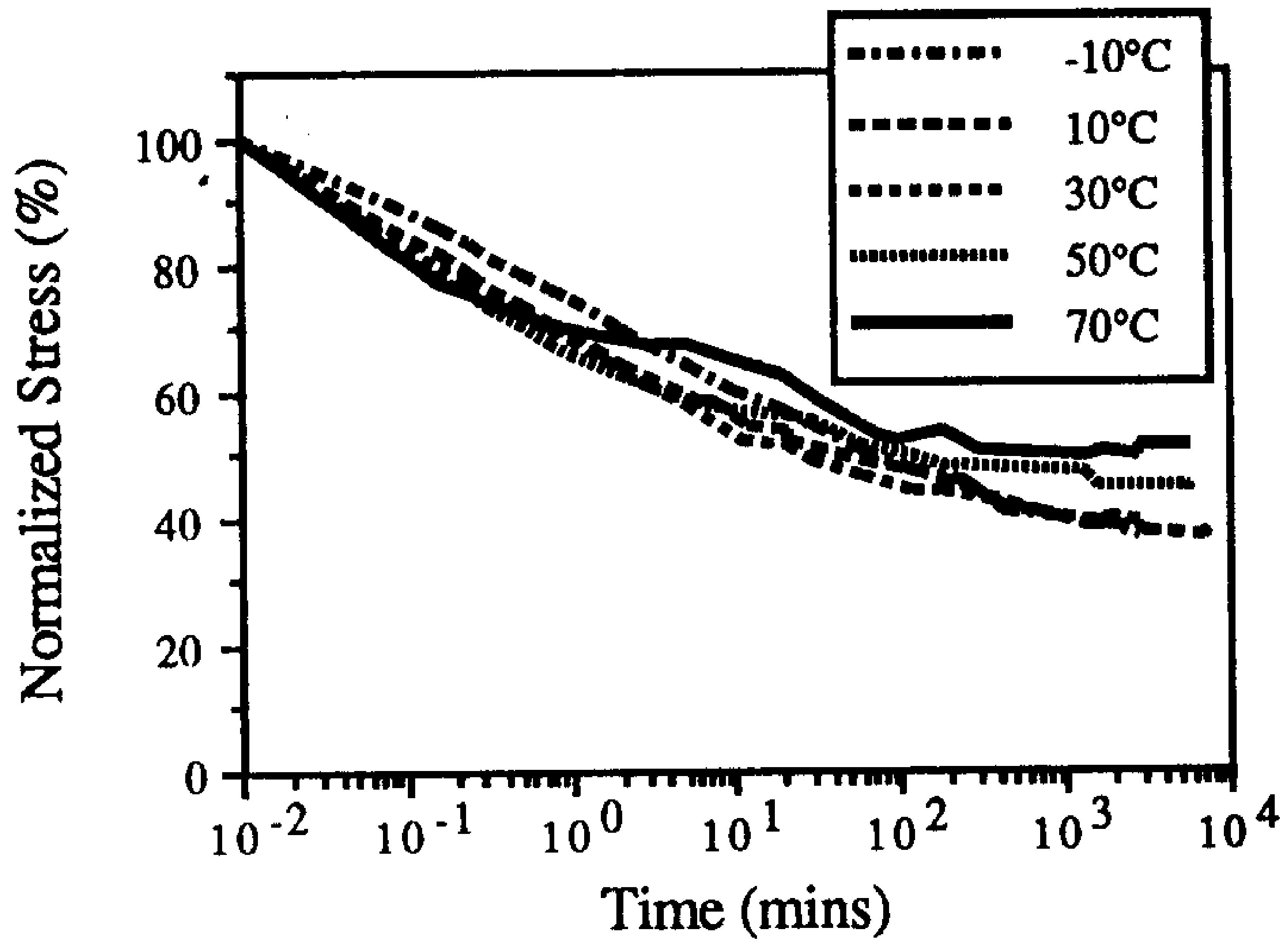

Figure 6 Normalized time-dependent stress of 1.5 mm HDPE geomembrane corresponding to initial strain level of 3% of strain at various temperatures.

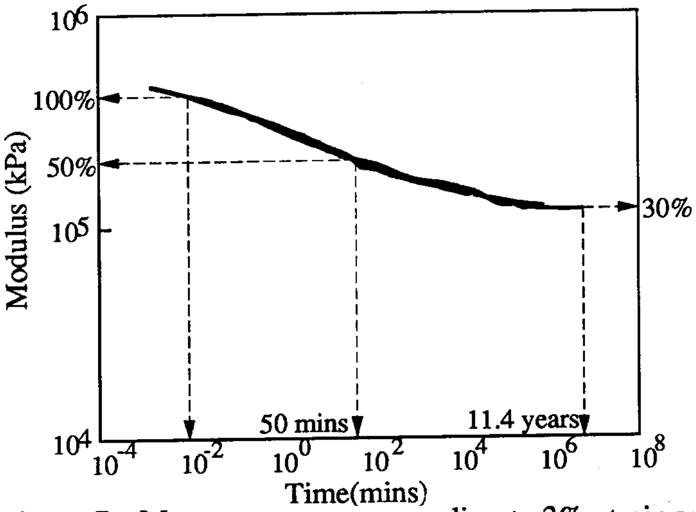

Figure 7 Master curve corresponding to 3% strain and a reference temperature of 10°C (From data of Figure 5).

Table 1 Summary of information generated from master curves corresponding to 3% strain at reference temperatures of -10, 10 and 30°C.

Ref. Temp. (°C)	T_{50}* (mins)	Residual Stress (% of $\sigma_{initial}$)
–10°C	100	25% @ 133 years
+10°C	50	30% @ 11.4 years
+30°C	30	35% @ 0.8 years

T_{50}* = Time required to reach 50% stress relaxation

Based on the T_{50} data shown in Table 1, HDPE geomembranes relax faster at higher temperatures. Thus test methods requiring a stipulated performance of geomembranes in a stress relaxation mode, must be performed under very careful temperature control. It should also be taken into consideration that the initial stress level will be very much higher at lower temperatures all other things being equal. Also seen from Table 1 is that there is a considerable amount of residual stress remaining even after very long time periods at low temperatures.

5 CONCLUSIONS

This study presents the effects of stress, strain, time and temperature of HDPE geomembranes in a stress relaxation testing mode. The following conclusions can be made:

- Different testing protocols were evaluated for performing stress relaxation tests as well as a number of methods to present data resulting from these tests.
- While different geomembranes will undoubtedly respond differently than the HDPE studied, the strong dependence of stress relaxation on temperature is clearly evident.
- The normalized stress relaxation curves (instantaneous stress/initial stress) versus time at a given temperature appear to fall reasonably well on a unique curve independent of stress and strain.
- The limits of linearity in the stress-strain relations have been determined as a function of stress, strain, time at various temperature. Therefore, it is likely that Boltzman's superposition principle of viscoelasticity can be used mathematically to estimate creep curves from the stress relaxation curves.
- For the 1.5 mm HDPE geomembrane evaluated in this study it was seen that increasing temperature decreases the time to reach 50% stress relaxation.
- This study has shown that the time-temperature principle of polymer viscoelasticity is valid for this particular HDPE geomembrane. Thus if modulus versus time curves are determined for short term periods at various temperatures, the data can be time-temperature shifted many years into the future.

In closing, it must be said that all the concerns of stress relaxation testing of geomembranes have not been solved, but a beginning has been made, where only scant data and few ideas existed before.

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