Accelerated Degradation of Recycled Plastic Piling in Aggressive Soils

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Abstract: Fiber-reinforced polymer composites represent an alternative construction material without many of the performance disadvantages of traditional materials. The use of fiber-reinforced polymer as a pile material can eliminate deterioration problems of conventional piling materials in waterfront environments and aggressive soils. This paper presents the preliminary results of an experimental study conducted to assess the durability of piling made of recycled plastics in aggressive soils for long-term usage in civil infrastructure applications. An accelerated testing protocol permitting prediction of the behavior of plastic piles was developed. Specimens were exposed to solutions with fixed acidic, basic, and neutral pH at elevated temperatures. Compressive strength was used as an index to quantify the degradation of the specimens. An Arrhenius model was used to predict the service life of the product.

INTRODUCTION

The deterioration of timber, concrete, and steel piling systems costs the United States nearly $1 billion per year for repair and replacement (Lampo et al. 1998). The durability of concrete and corrosion of steel are serious hindrances to construction in aggressive soils and waterfront environments. In the case of marine pilings, actions required by the federal Water Pollution Control Act of 1972 gradually rejuvenated many of the nation's waterways and harbors. A side effect of this environmental benefit is the return of marine borers, which started to attack the untreated timber piles that support many of the nation's harbor piers (Iskander and Stachula 1999). At the same time, over 4 billion kg of rigid plastic containers are produced annually in the United States (Lampo 1995). Most of these containers are high-density polyethylene (HDPE) milk jugs and polyethylene terephthalate soda bottles. As much as 3 billion kg of these materials are buried in landfills, and the rest are recycled. Recycled fiber-reinforced polymer (FRP) composites represent an alternative construction material without many of the performance disadvantages of traditional construction materials.

Composite piling products have been used to a limited degree, or experimentally, throughout the nation for waterfront barriers, fender piles, and bearing piles for light structures (Iskander and Hassan 1998). Most composite piling products are made of recycled HDPE with E-glass or steel reinforcement. Additives are also used to improve the mechanical properties, durability, and ultraviolet (UV) protection of FRP.

Polymers have been successfully used in soil for five decades by the pipe, power, and telecommunication industries. In the last 20 years geosynthetic materials have also been used extensively in civil engineering construction with apparent success. Nevertheless, degradation of buried plastics in corrosive soil environments has been reported (Salman et al. 1997).

The paper presents the preliminary results of an experimental study conducted to assess the durability of piling made of recycled plastics in aggressive soils for long-term usage in civil infrastructure applications. Specimens were exposed to solutions with fixed acidic, basic, and neutral pHs at elevated temperatures. Compressive strength was used as an index to quantify the degradation of the specimens. An Arrhenius model was used to predict the service life of the product.

DEGRADATION OF POLYMERS

Applications such as plastic piles, solid-waste liner systems, landfill cover systems, retaining walls, and slope reinforcement require service lifetimes of 100+ years. Accordingly, degradation of polymeric materials buried in soils is an important concern due to their lack of a long-term track record. The degradation of recycled polymers in aggressive conditions depends on the macromolecular structure and the presence of additives and contaminants commonly found in recycled plastics. Most plastic piles used in construction contain additives and stabilizers that improve the resistance of the polymers to degradation. However, these additives can be susceptible to leaching or to biological attack, thereby leaving the plastic pile material unprotected. The principal result of degradation is the loss of mechanical strength, which may lead to unfavorable engineering performance and a shorter life cycle.

Environmental conditions that contribute to chemical degradation in polymeric materials include elevated temperature, UV radiation, and exposure to oxygen, moisture, and acidic or basic environments. The relative importance of these factors is determined by the usage of the material. Salman et al. (1997) identified the main mechanisms that degrade geosynthetic polymers as either hydrolysis for polyester-based geosynthetics or thermo-oxidation for polyolefin-based geosynthetics.

Hydrolytic Degradation

Hydrolysis occurs when positively charged hydrogen ions (H^+) in acidic or negatively charged hydrogen ions (OH^-) in alkaline media attack the ester linkage, thus breaking the polyester chain. This reduces the polymer chain length and alters its molecular weight distribution, which directly impacts the strength of the material. In addition to chain breakage, hydrolysis in alkaline media causes surface erosion of polyesters, which is manifested by weight loss. The rate of hydrolysis is slow at ambient temperatures but is not negligible, considering the typical lifetime of a civil engineering structure. Accordingly, hydrolysis may affect fiberglass reinforcement in FRP piling, which is typically made of glass/vinyl ester.

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Thermooxidation Degradation

Chain breakage and the associated reduction in strength of polyolefin-based materials depend on the presence of oxygen as well as temperature levels (Chien and Boss 1967). Thermooxidation affects polyolefin plastics such as HDPE, which is the main constituent of structurally reinforced plastic matrix, glass-reinforced plastic, and steel-pipe core piling. The rate of thermal oxidation is slow at ambient temperatures. Salman et al. (1997) estimated that approximately 50 years are required before a statistically significant change in the strength of polyolefin geosynthetics is observed at 20°C. An additional 35 years are required for a 50% loss in strength. Geosynthetics have significantly smaller thickness than piling materials, and accordingly thermo-oxidation of composite piling is expected to occur over a significantly longer duration.

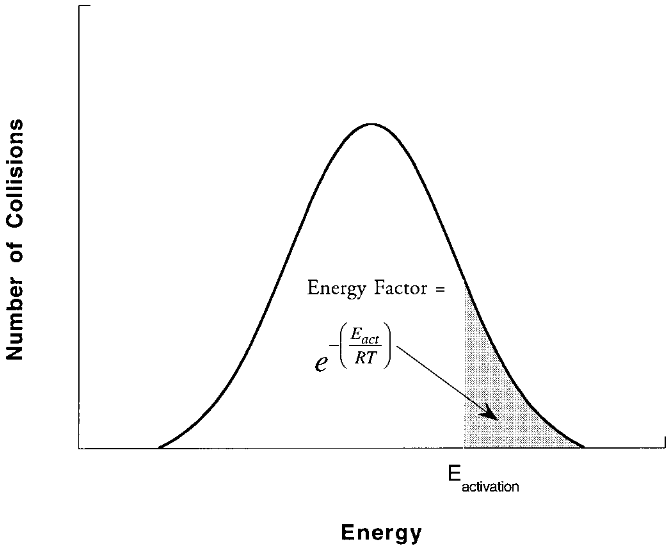

FIG. 1. Distribution of Reaction Energy in Ideal Gas

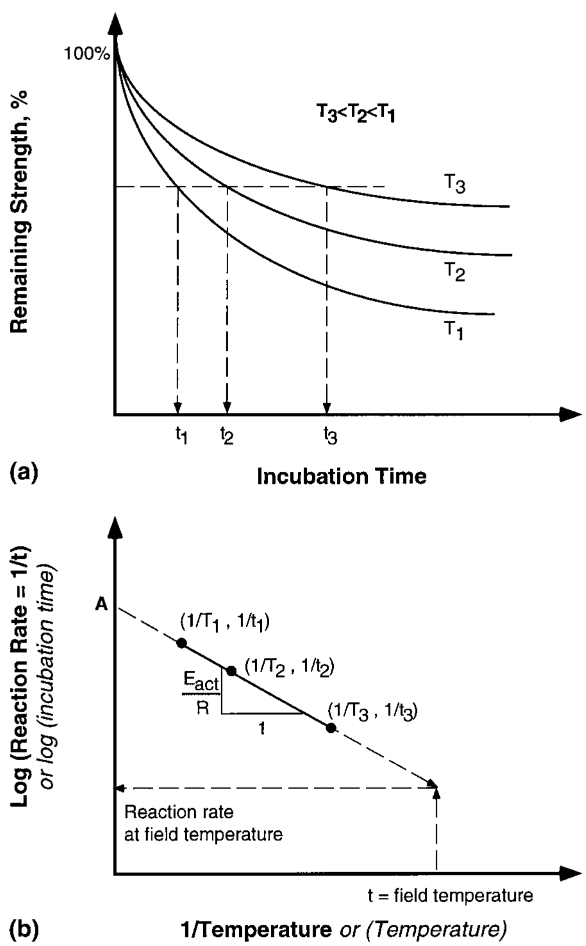

FIG. 2. Arrhenius Model: (a) Change in Measured Experimental Property with Time for Different Incubation Temperatures. (b) Derived Arrhenius Plot

TABLE 1. Environmental Conditions of Reactors

Reactor number	Temperature (degrees C)	Media	pH
R1	55	Acidic	2
R2	40	Neutral	7
R3	55	Neutral	7
R4	75	Neutral	7
R5	55	Alkaline	12
R6	40	Alkaline	12
R7	75	Alkaline	12
R8	40	Acidic	2
R9	75	Acidic	2

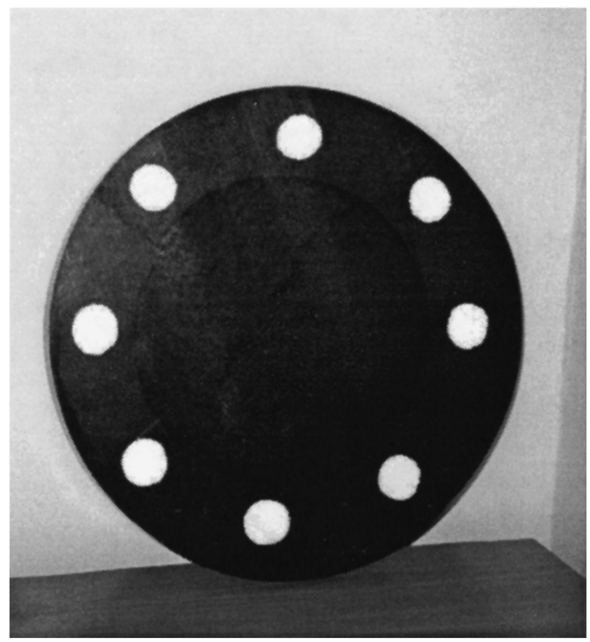

FIG. 3. Cross Section of Seapile (Note Variation of Shade Indicating Presence of Core at Center of Pile)

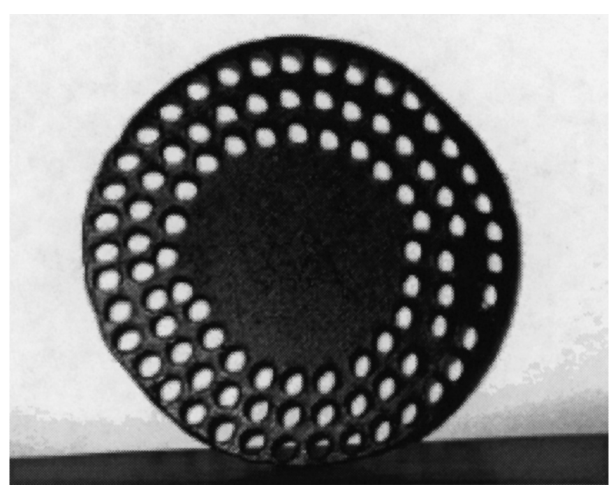

FIG. 4. Pile Core Showing Location of Punched Specimens

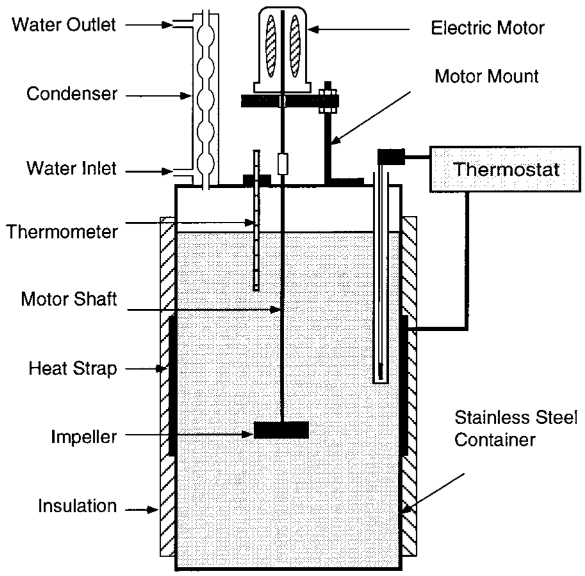

FIG. 5. Schematic of Test Reactor

ARRHENIUS MODELING

An Arrhenius model was used to predict the service life of the tested material. This methodology was first used in civil engineering by Koerner et al. (1992) to predict the degradation of thin geosynthetic polymeric materials used in landfill liners and covers. The methodology was originally developed for gases, in which chemical reactions were observed to proceed more rapidly at higher temperatures than at lower ones (Arrhenius 1912). It uses high-temperature incubation of test specimens in order to accelerate degradation. The experimental behavior of the specimens, at a site-specific lower temperature, is then extrapolated from the accelerated degradation data. This assumes that the material's behavior at the high temperature can be extrapolated to the lower temperature of practical interest.

According to Morrison and Boyd (1978), the rate of reaction for gases is equal to the product of (1) collision frequency: total number of collisions between reactants per unit volume per unit time; (2) energy factor: fraction of collisions that have sufficient energy to cause a reaction [for a reaction to occur, the collision energy must surmount an energy barrier referred to as the activation energy (E_{act})]; and (3) orientation factor: fraction of collisions that have proper orientation.

The collision frequency and orientation factor are independent of temperature and can be bracketed as a constant term A. Accordingly, the energy factor is the most important factor in determining reaction rates as a function of temperature. The collision energies follow the traditional Gaussian distribution (Fig. 1). The fraction of particles in Fig. 1 having energies greater than the activation energy is given by Koerner et al. (1992):

$$\text{energy factor} = e^{[-(E_{act}/RT)]} \tag{1}$$

where R = gas constant and T = temperature of the reaction in degrees Kelvin. The rate of reaction (R_r) can thus be written as

$$R_r = Ae^{[-(E_{act}/RT)]} \tag{2}$$

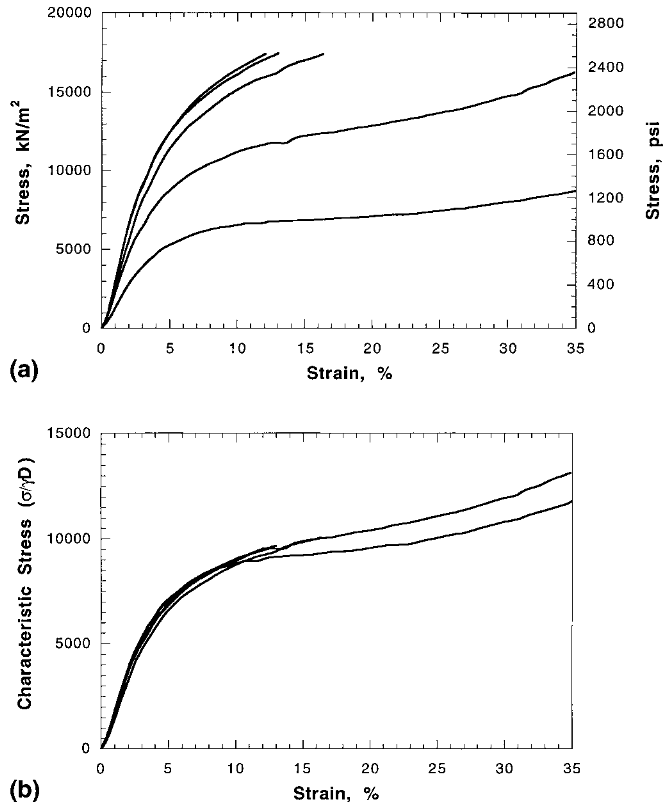

FIG. 7. Data Normalization: (a) Conventional Stress-Strain Curves. (b) Characteristic Strength versus Strain Curves for Conventional Stress-Strain Curves Shown in (1)

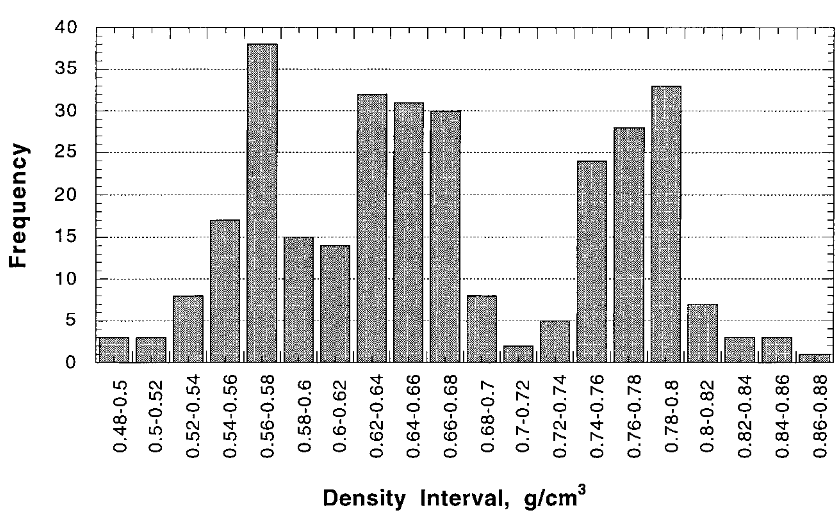

FIG. 6. Density Distribution of Tested Specimens

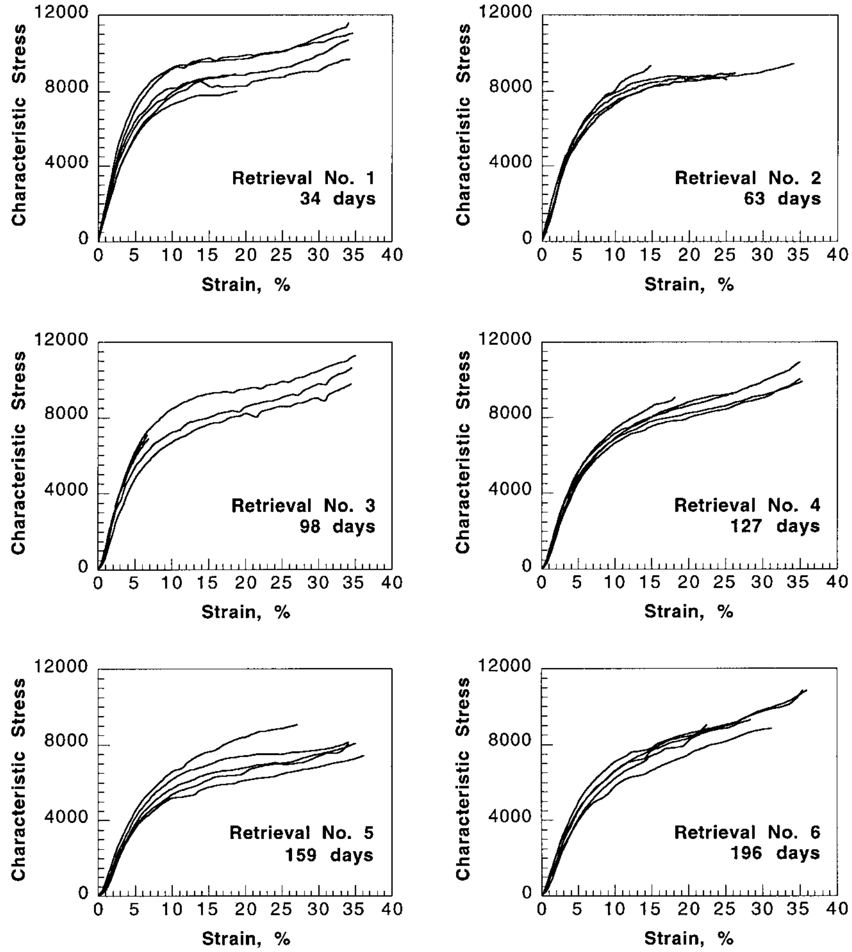

FIG. 8. Characteristic Strength versus Strain Curves for Reactor No. 9 (pH = 2, Incubation Temperature = 75°C)

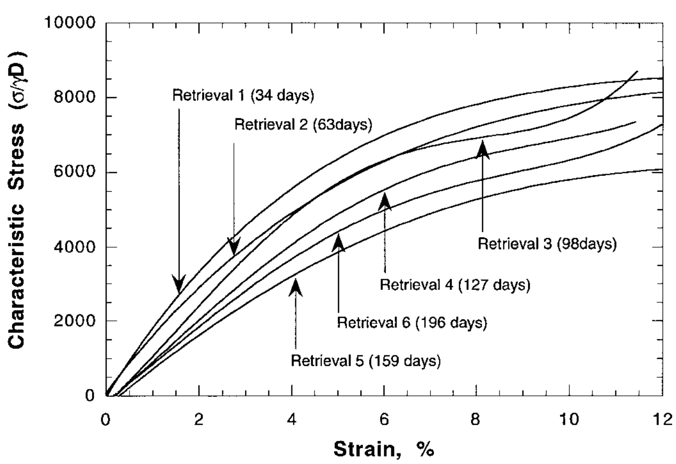

FIG. 9. Average Characteristic Stress versus Strain Curves for Reactor No. 9 (pH = 2, Incubation Temperature = 75°C)

Taking the natural logarithm of both sides of (2) yields the following straight-line equation, shown in Fig. 2, which is known as an Arrhenius plot.

$$\ln R_r = \ln A - \left(\frac{E_{\rm act}}{R}\right)\frac{1}{T} \qquad (3)$$

Assuming that the term ($E_{\rm act}/R$) remains constant, the reaction rate at a low site-specific temperature can be predicted using high-temperature incubation data. The equation has been used to predict long-term degradation of a wide range of materials, including many polymeric materials.

Any relevant strength test can be used as an index to quantify degradation; in this study we used compressive strength. The rate of reaction, R_r, is obtained by determining the time taken to reach a specified loss of strength at an incubation temperature, T. An Arrhenius plot can be constructed by plotting the rates of reactions against the corresponding incubation temperatures for the same specified strength loss (Fig. 2). At least three but preferably more data points are required to ensure that the relationship is linear. The Arrhenius plot is extrapolated to any site-specific temperature in order to obtain the reaction rate at that temperature.

Arrhenius modeling of solid structural members is subject to a number of limitations. First, it presumes that reactions can freely occur between all the solid molecules and the aggressive media, which assumption is obviously invalid for structural members that are exposed to aggressive media at the surface only. Second, more than one mechanism may cause degradation of a given mechanical, physical, or chemical property over a wide temperature range resulting from the difference between incubation temperature and site-specific temperature. Accordingly, recycled polymers may be subject to multiple activation energies (and reaction rates), instead of a single one, due to the presence of additives and impurities.

TESTING PROGRAM

Aqueous solutions were used to simulate aggressive soils in the lab. Three different solutions were used to represent neutral (pH = 7), acidic (pH = 2), and alkaline (pH = 12) environments. In order to achieve measurable changes of strength within the duration of the experiment, specimens exposed to each pH level were aged at three elevated temperatures (40, 55, and 75°C), resulting in a total of nine different degradation environments (Table 1).

Test Specimens

Test specimens were cut out of Seapile (Seaward International, Inc., Clearbrook, Va.) (Fig. 3). Seapile (1994) is produced in two stages. First, a core is produced from recycled plastic. Next, reinforcement is added and additional recycled HDPE is molded around the core. Seaward provided us with saw-cut cross sections, 10 in. in diameter and approximately 1 in. thick, that were taken from the core of the pile's cross section. Cylindrical specimens 12.7 mm in diameter and 25.4 mm long were punched out of these cores using a specially designed tool (Fig. 4). The resulting specimens have a length-to-diameter ratio of 2:1, which meets the requirements of the ASTM D-695 standard. The weights, lengths, volumes, and densities of all specimens tested in this program were recorded.

Seapile is foamed at the center and solid at the edges. Three consecutive rows of specimens were taken from each cross section to avoid excessive variation in the mechanical properties of the specimens (Fig. 4).

Testing Matrix

A total of 54 retrievals, in addition to the as received specimens, were scheduled for one retrieval per reactor each month for 6 months. Each retrieval contained an average of six specimens for testing in unconfined compression, per the ASTM D 695-96 *Standard Test Method for Compressive Properties of Rigid Plastics*.

A code number was assigned to each specimen in order to keep track of the data and to make it easier to correlate and

TABLE 2. Incubation Time versus Characteristic Strength Values at 1% Strain

Time	Acidic (pH = 2)			Neutral (pH = 7)			Alkaline (pH = 12)		
(days)	40°C	55°C	75°C	40°C	55°C	75°C	40°C	55°C	75°C
0	1,596	1,596	1,596	1,596	1,596	1,596	1,596	1,596	1,596
34	2,114	1,714	1,925	1,818	1,768	1,873	1,748	1,819	1,783
63	1,472	1,660	1,611	1,647	1,636	1,536	1,769	1,762	1,879
98	1,407	1,181	958	2,296	1,896	1,022	1,564	1,639	1,229
127	1,550	1,427	792	1,678	1,294	1,303	1,390	1,828	1,418
159	1,341	1,529	577	1,361	1,018	974	1,556	1,025	924
196	1,660	1,245	774	1,468	907	859	1,759	1,382	895

TABLE 3. Incubation Time versus Characteristic Strength Values at 2% Strain

Time	Acidic (pH = 2)			Neutral (pH = 7)			Alkaline (pH = 12)		
(days)	40°C	55°C	75°C	40°C	55°C	75°C	40°C	55°C	75°C
0	2,925	2,925	2,925	2,925	2,925	2,925	2,925	2,925	2,925
34	3,610	3,101	3,429	3,168	3,215	3,389	3,082	3,262	3,263
63	2,877	3,127	2,934	3,134	3,004	2,756	3,192	3,129	3,417
98	3,393	2,915	2,442	4,020	3,422	2,864	3,495	3,368	3,225
127	3,539	3,313	2,018	3,728	3,180	3,220	3,342	3,628	3,344
159	3,157	3,574	1,478	3,082	2,894	2,668	3,667	2,822	2,300
196	3,705	3,011	1,860	2,978	2,757	2,488	3,850	3,403	2,236

TABLE 4. Incubation Time versus Characteristic Strength Values at 4% Strain

Time	Acidic (pH = 2)			Neutral (pH = 7)			Alkaline (pH = 12)		
(days)	40°C	55°C	75°C	40°C	55°C	75°C	40°C	55°C	75°C
0	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927	4,927
34	5,428	5,110	5,555	4,892	5,332	5,575	4,898	5,296	5,426
63	5,226	5,378	4,909	5,425	5,069	4,456	5,189	5,010	5,663
98	6,175	5,990	4,829	6,340	5,582	5,799	6,148	6,279	6,638
127	6,217	6,319	4,137	6,732	6,202	5,930	6,237	6,303	6,179
159	5,866	6,655	3,281	5,906	6,055	5,474	6,642	5,826	4,646
196	6,395	5,940	3,705	5,612	6,022	5,237	6,514	6,537	4,419

TABLE 5. Incubation Time versus Characteristic Strength Values at 8% Strain

Time	Acidic (pH = 2)			Neutral (pH = 7)			Alkaline (pH = 12)		
(days)	40°C	55°C	75°C	40°C	55°C	75°C	40°C	55°C	75°C
0	7,105	7,105	7,105	7,105	7,105	7,105	7,105	7,105	7,105
34	7,074	7,142	7,775	6,338	7,505	7,766	6,740	7,341	7,484
63	7,678	7,505	7,144	7,469	7,284	6,074	7,022	6,846	7,978
98	8,380	8,826	7,053	8,673	7,653	8,333	8,383	8,941	9,009
127	8,500	8,679	6,354	8,882	8,698	8,342	8,488	8,569	8,404
159	8,040	8,855	5,197	8,099	9,060	7,955	8,696	8,274	6,824
196	8,578	8,220	5,806	8,189	8,932	7,834	8,768	8,880	6,793

cross-reference the different variables. For instance, specimen number 361 denotes reactor number 3, retrieval number 6, and specimen number 1 in that retrieval.

Experimental Setup

Nine stainless steel reactors were set up, as shown in Fig. 5. Four 60 L reactors and five 95 L reactors were used in order to utilize the available apparatus. Each reactor consists of a stainless steel barrel surrounded by a heating strap and fiberglass insulation. A stainless steel cover was fastened on top of the reactor by means of a clamp.

A closed-loop system consisting of a thermocouple and a thermostat connected to the heat strap was used to maintain a constant temperature in each reactor. Temperature was independently monitored with a mercury thermometer.

A condenser was mounted on top of each reactor to minimize evaporation losses and maintain constant pH levels. Condensers consist of two glass tubes, internal and external. The internal tube receives vapor from the reactor, which is condensed by tap water flowing in the external tube. The pH was routinely checked with an electronic probe and adjusted when necessary.

An electric motor connected to a stirrer was mounted at the top of each reactor in order to mix the liquid and achieve uniform temperature and pH in the reactor. The motor stirred the liquid at a rate of 48 rpm.

During the incubation period, specimens for each retrieval were kept in bags that were custom-made from polymeric window-screen material. The bags were tied to a stainless-steel frame inserted in each reactor to prevent the bags from floating to the surface of the liquid.

Compression Tests

Compression testing was selected as an index for comparing degradation results because piles are subjected mainly to compression. Specimens were tested in unconfined compression according to the ASTM D 695-96. A computerized loading frame permitting displacement-controlled compression testing was used. The specimens were tested at a strain rate of 15%/min to a strain of 35%. Load and deformation were measured electronically.

TEST RESULTS

The specimens comprising each retrieval were weighed before and after incubation. No measurable change in the dry weight was observed over the incubation period. These results could indicate that surface erosion did not take place and that the degradation process, if any, is caused by chain breakage only.

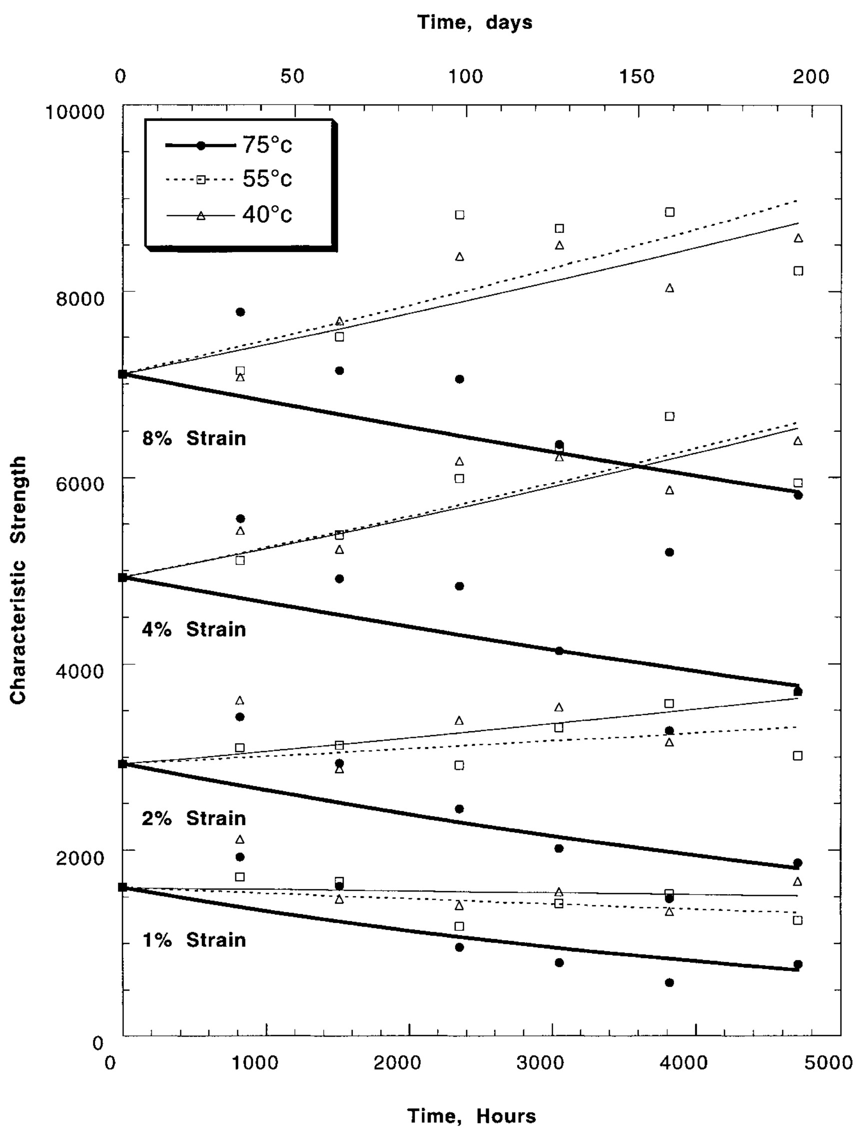

FIG. 10. Incubation Time versus Characteristic Stress for Acidic Environment

Data Presentation

When the stress versus strain data were first plotted, a large scatter was observed for specimens in the same retrieval. Variation was attributed to the difference in densities among the specimens caused by the manufacturing process for Seapile, which, like many polymeric structural members, is foamed at the center and solid at the edges. In addition, the manufacturing process could have resulted in variation in strength of the parent material across the cross section. The density distribution of all the specimens used in this study is shown in Fig. 6. The specimens can be divided into three groups: light (0.48–0.60 g/cm^3), medium (0.60–0.70 g/cm^3), and heavy (0.70–0.88 g/cm^3). These three groups presumably were formed because the specimens were taken from three consecutive rows from the circular core.

Several methods to normalize the data and reduce scatter were investigated (Hassan 1999). The nondimensional term $\sigma/\gamma R$ was found to reduce scatter the most (Fig. 7), where σ is the measured stress, γ is the density of the specimen, and R is the radial distance from the center of the core to the location of the specimen. The term $\sigma/\gamma R$ is referred to in this paper as the Characteristic Stress, and it will be used to present test results throughout.

Accelerated Degradation Test Results

Approximately 300 compression tests were performed. Space limitations prevent presentation of the complete test results, so data are presented for one reactor only. The complete test results for all reactors are available in Hassan (1999). The characteristic stress-strain curves for all specimens retrieved from Reactor No. 9 are shown in Fig. 8. Six average curves were calculated for each of the retrievals shown in Fig. 8. The average curves (Fig. 9) are simply numerical averages of the characteristic stress-strain curves of all the specimens tested in any retrieval.

Specimens tested in this study did not exhibit a defined failure point, stress continued to increase with strain, and no peak was observed. For this reason four representative strains at 1, 2, 4, and 8% were selected for further investigation. Tables 2–5 show the incubation time versus the characteristic stress for the nine reactors at the selected strains.

DATA ANALYSIS

One of the main assumptions involved in the Arrhenius modeling is that the material's behavior in the high-temperature incubation range is constant within this range and can be extrapolated to the lower-temperature behavior of practical in-

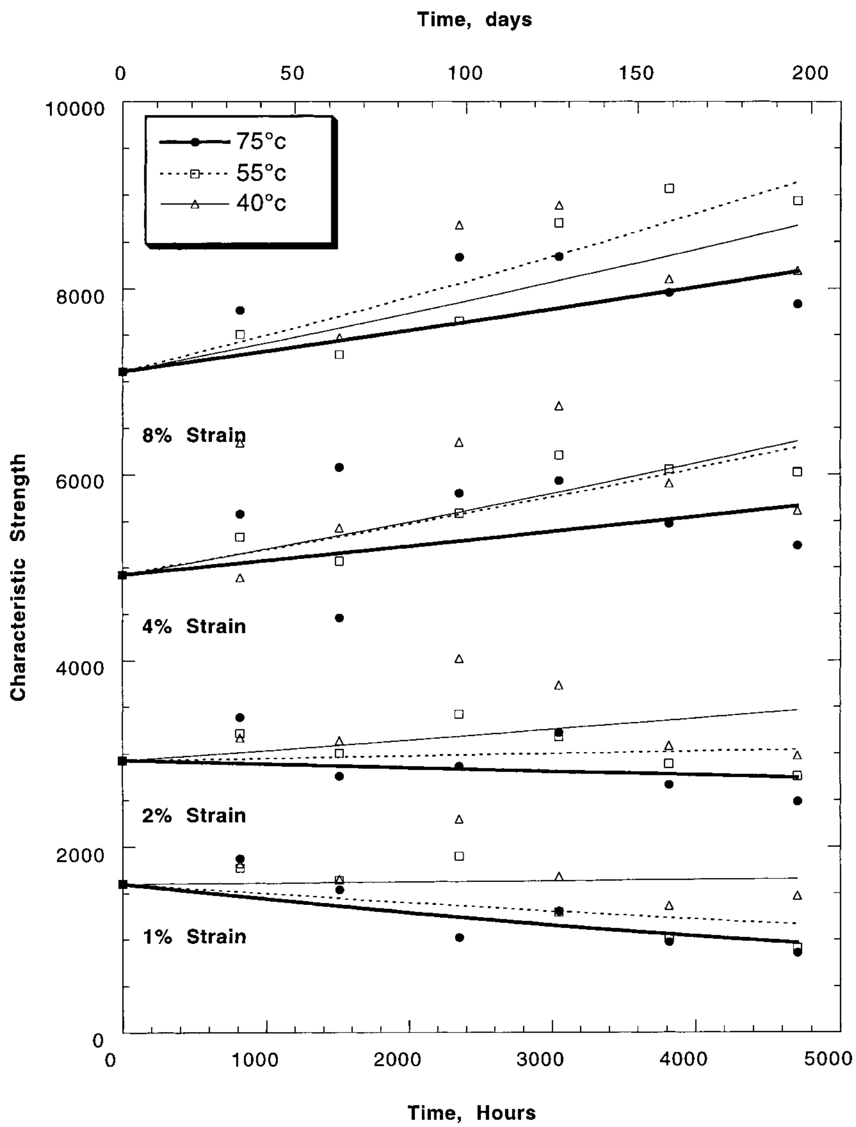

FIG. 11. Incubation Time versus Characteristic Stress for Neutral Environment

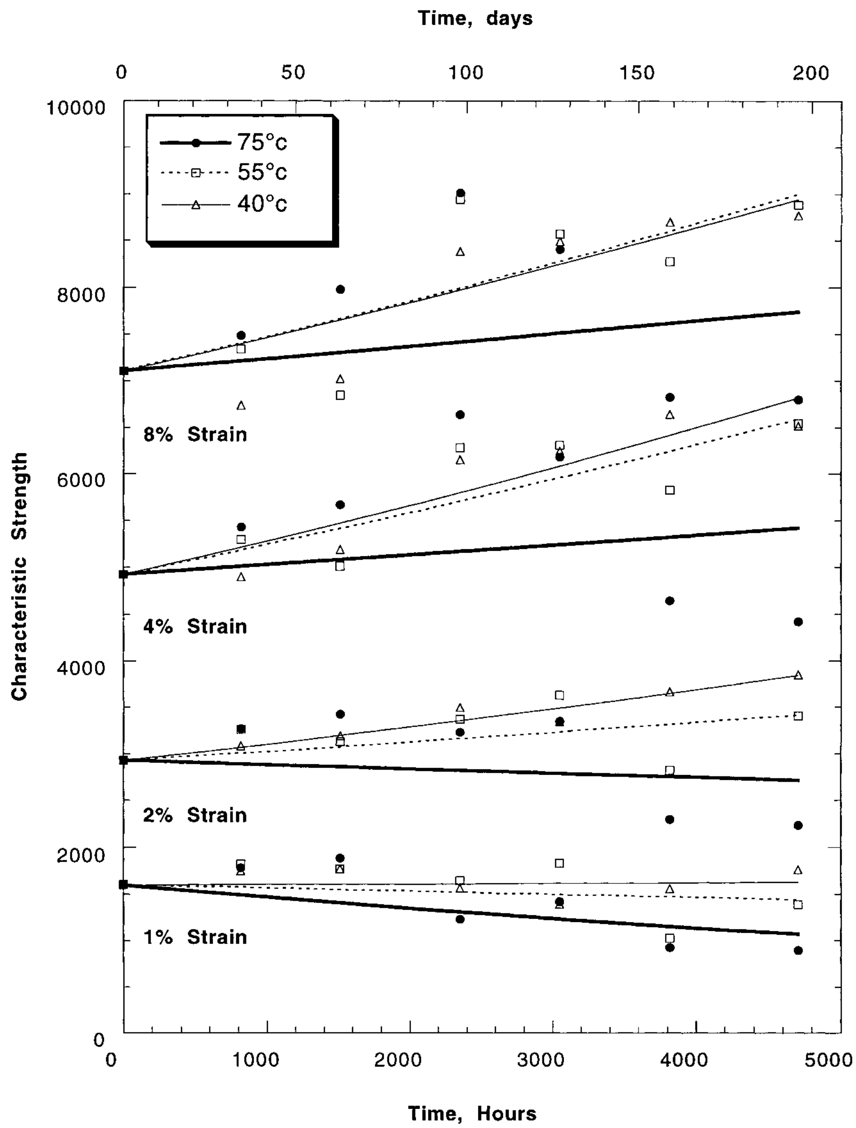

FIG. 12. Incubation Time versus Characteristic Stress for Basic Environment

terest. Most of the results violated this requirement, and it was observed that some specimens gained strength, particularly at high strain levels. This can be illustrated in the curves shown in Figs. 10–12. In general, a reduction of strength was noted for the 1% strain curves, which could indicate that high-temperature incubation caused microcracks to close; this appears to influence the strength at higher strains only. Accordingly, only characteristic strengths measured at 1% strain were selected for Arrhenius modeling.

Exposure to the acidic environment had a consistent measurable degradative effect on the material, particularly at the highest incubation temperature. Incubation in alkaline or neutral environments had mixed effects, and the Arrhenius model could not be applied to them.

Fig. 10 was used to construct the Arrhenius plot in Fig. 13, which shows the time needed to reach a given strength loss at a corresponding incubation temperature. The 6-month incubation period was too short to reach the prescribed strength losses at lower temperatures. Accordingly, data for strength loss at lower temperatures were extrapolated by substituting in the exponential-curve fit equations shown in Fig. 10 and indicated in Fig. 13.

The remaining characteristic strength at 1% strain at a service temperature of 25°C (Fig. 14) was obtained by extending the Arrhenius plots shown in Fig. 13 to 25°C and reading the corresponding time on the *y*-axis. Based on these preliminary test results, an estimated 25% loss in resistance at 1% strain is expected to take 14 years for coupon specimens exposed to pH = 2 at 25°C. If the reaction rates remain constant, the compressive-strength half-life of the material (50% loss) is estimated to occur in 33 years under the same conditions.

LIMITATIONS OF STUDY

Several factors indicate that Seapile is expected to have a higher resistance to aggressive media than the tested specimens. First, this study was conducted on small-scale specimens, which were exposed to aggressive media at the surface. Piling is typically 25 times larger in diameter than the tested specimens. Accordingly, degradation of real piles is expected to occur over a considerably longer duration. Second, specimens were punched out from the foamed core, whereas the material that surrounds the core is much denser and of better quality, particularly at the outer perimeter.

More than one degradation mechanism could have occurred over the wide range of temperatures used in this study, particularly because recycled plastics containing additives and impurities were used. Arrhenius modeling assumes that only one degradation mechanism is present and could be extrapolated over the full temperature range of the study. In addition, some

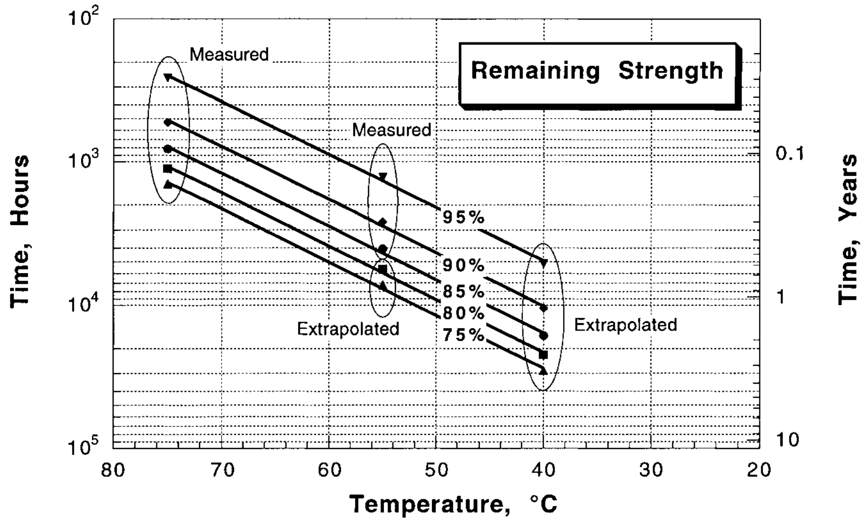

FIG. 13. Arrhenius Plot for Different Remaining Strengths at 1% Strain (Acidic Environment, pH = 2)

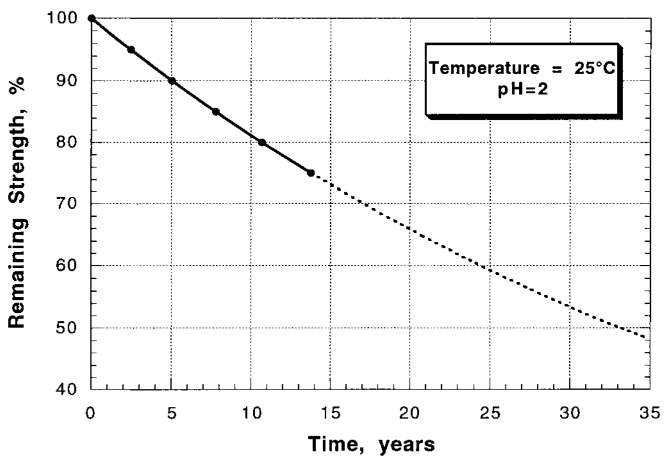

FIG. 14. Remaining Characteristic Resistance at 1% Stain at Room Temperature (Acidic Environment, pH = 2)

mechanisms may become operative only at elevated temperatures; thus, care must be taken when accelerating degradation with exposure to elevated temperature. As a result, we were able to apply the Arrhenius model to predict the strength loss at small strains for specimens incubated in severe acidic environments only.

CONCLUSIONS

The 6-month incubation period over the length of the study was too short to derive final conclusions. However, the following preliminary conclusions can be made based on the data observed so far:

Exposure to the acidic environment (pH = 2) had a consistent measurable degradative effect on recycled HDPE, particularly at the highest incubation temperature. Incubation in alkaline or neutral environments had mixed effects, and the Arrhenius model could only be applied to data obtained for incubation in acids.

A 25% loss in resistance at 1% strain is expected to take 14 years for coupon specimens exposed to pH = 2 at 25°C. Seapile is expected to have a higher resistance to aggressive media than the tested specimens because of its larger diameter and enhanced material properties at the surface.

ACKNOWLEDGMENTS

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