

Durability of Recycled FRP Piling in Aggressive Environments

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by

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Abstract. Fiber reinforced polymer (FRP) composites represent an alternative construction material without many of the performance disadvantages of traditional materials. The use of FRP as a pile material can eliminate deterioration problems of conventional piling materials in water front environments and aggressive soils. This paper presents the results of one-year 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 & 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. An estimated 25% loss in resistance at 10% strain, is projected to take 21 years for coupon specimens incubated at pH = 2 and 25 years for coupon specimens incubated at pH = 12.

INTRODUCTION

The deterioration of timber, concrete, and steel piling systems costs the United States nearly \$1 billion per year for repair and replacement (1). The durability of concrete and corrosion of steel are serious hindrances to construction in aggressive soils and waterfront environments. In the case of marine piling, 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 (2). At the same time, over 8.4 billion pounds of rigid plastic containers are produced annually in the United States (3). Most of these containers are made of high-density polyethylene (HDPE) milk jugs, and polyethylene-terephthalate (PET) soda bottles. As much as 7.2 billion pounds of these materials are buried in landfills and the rest is recycled.

Composite piling products have been used to a limited degree throughout the nation for waterfront barriers, fender piles, and bearing piles for light structures (4). Most composite piling products are made of recycled HDPE with E-glass or steel reinforcement. Chemical 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 twenty years geosynthetic materials have also been extensively used in civil engineering construction with success. Nevertheless, degradation of buried plastics in corrosive soil environments has been reported (5).

This paper presents the 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 tested specimens.

DEGRADATION OF POLYMERS

Usage of polymeric materials in civil infrastructure requires 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, the presence of chemical additives, and contaminants commonly found in recycled plastics. Most plastic piles used in construction contain additives and stabilizers, which 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 which contribute to chemical degradation in polymeric materials include elevated temperature, UV radiation, exposure to oxygen, moisture, and pH. The relative importance of these factors is determined by the usage of the material. Salman *et al.* (5) identified the main mechanisms that degrade geosynthetic polymers as either hydrolysis for polyester-based polymers, or thermo-oxidation for polyolefin-based polymers.

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* (6) to predict the degradation of thin geosynthetic polymeric materials used in landfill liners and covers. The methodology was originally developed for gases where chemical reactions were observed to proceed more rapidly at higher temperatures than at lower ones (7). It uses high-temperature incubation of test specimens in order to accelerate degradation. Next, the experimental behavior of the specimens, at a site-specific lower temperature, is 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 (8), the rate of reaction for gases is equal to the product of:

- *Collision Frequency* which is total number of collisions between reactants per unit volume per unit time
- *Energy Factor* which is the 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})
- *Orientation Factor* which is the 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 distribution of collision energies is assumed to follow the traditional gaussian distribution curve shown in Fig. 1. The fraction of particles in Fig. 1 having energies greater than the activation energy is given by Koerner (6):

$$\text{Energy Factor} = e^{-\left(\frac{E_{act}}{RT}\right)} \quad (1)$$

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

$$R_r = Ae^{-\left[\frac{E_{act}}{RT}\right]} \quad (2)$$

Taking the natural logarithm of both sides of eq. 2 yields the following straight line equation shown in Fig. 2, which is known as an *Arrhenius Plot*.

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

Assuming that the term (E_{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 the compressive strength was used. 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 is obviously invalid for structural members which 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. Third, resins may undergo subtle changes on heating and can become susceptible to more deterioration or gain in strength than

they would experience at service temperature. Nevertheless, Pritchford (9) stipulated that the predictions obtained from high temperature incubation, overestimate the magnitude of degradation when applied to lower temperatures.

TESTING PROGRAM

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

Test Specimens

Seapile™ which is a product of Seaward International, Inc. (10) was used (Fig. 3). Seapile™ is produced in two stages. First, a core made of recycled HDPE is produced. Next, structural reinforcement is added & additional recycled HDPE is molded around the core. Seaward mixes proprietary additives and fiberglass reinforcement with the HDPE to enhance the properties of the pile matrix. Seaward provided us with saw cut cross-sections, 10 inches in diameter and approximately 1 inch thick. These cross sections were taken from the core of the pile's cross-section. Cylindrical specimens 0.5-in diameter x 1-in long were punched out of these cores. 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 108 retrievals, in-addition to the as-received specimens, were scheduled at a rate of one retrieval per reactor each month for 12 months. Each retrieval contained an average of 6 specimens for testing in unconfined compression.

Experimental Setup

Nine stainless steel reactors were set up, as shown in Fig. 4. Four 60-liter reactors and five 95-liter 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 the top of each reactor to minimize evaporation losses and maintain pH constant. Condensers consist of 2 glass tubes, internal and external. The internal tube receives vapor from the reactor, which is condensed by cold 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.

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 ASTM D 695 Standard Test Method for Compressive Properties of Rigid Plastics(11). 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 30%. Load and deformation were measured electronically.

TEST RESULTS

Data Presentation

When the stress vs. 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. This difference in densities is caused by the manufacturing procedure of Seapile™. Seapile™, 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 specimen used in this study is shown in Fig. 5. The specimens can be divided into 3 groups, light (0.48-0.60 gm/cm³), medium (0.60-0.70 gm/cm³), and heavy (0.70-0.88 gm/cm³). These three groups were formed presumably 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 non-dimensional term $\sigma/\gamma R$ was found to reduce scatter the most (Fig. 6). 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 the paper.

Accelerated Degradation Test Results

Approximately 700 compression tests were performed. Space limitations prevent presentation of the complete test results, so data is presented for one reactor only. Preliminary test results of this study were published in Iskander & Hassan (13). The complete test results for all reactors is available in Mohamed (14). Specimens did not exhibit a defined failure point so peak strength was defined at 10% strain.

The characteristic stress strain curves for all specimens retrieved from reactor No. 9 are shown in Fig. 7. For each retrieval individual tests are shown using thin solid lines, and the heavy dashed line represents a numerical averages of the data. The average characteristic strengths for the nine reactors at 10% strain are shown in table 2.

One of the main assumptions involved in the Arrhenius modeling is that the material's behavior at the high temperature incubation range is constant within this range and can be extrapolated to the lower temperature behavior of practical interest. Most of the results violated this requirement and it was observed that specimens incubated in water (pH = 7) gained strength with time (Fig. 8). This could have been caused by fusion of the polymer and closure of micro cracks. Therefore, the strength of the specimens incubated in acidic and alkaline environments were normalized by the strength of specimens incubated in the neutral environment, for the same incubation period (Fig. 9 & 10). Strength loss was observed at the 75°C and 55°C incubation temperatures only. The specimens incubated at 40°C exhibited an increase in strength relative to specimens incubated in water. This could have been caused by more than one degradation mechanism taking place over the wide range of temperatures used in this study, particularly because recycled plastics were used (9).

The Arrhenius plots shown in Fig. 11 and 12 were constructed using the data shown in Fig. 9 & 10, respectively. An Arrhenius plot shows the time needed to reach a given strength loss at a corresponding incubation temperature. The incubation period was too short to reach the prescribed strength losses at lower temperatures. Accordingly, data for strength loss at lower temperatures was extrapolated by substituting in the curve fit equations used in Fig. 9 & 10. Measured and extrapolated data are marked on Fig. 11 and 12.

The remaining relative resistance at 10% strain at a service temperature of 25°C (Fig. 13) was obtained by extending the Arrhenius plots shown in Fig. 11 and 12 to 25°C and reading the corresponding time on the y-axis. An estimated 25% loss in resistance at 10% strain, is expected to take 21 years for coupon specimens incubated at pH = 2 and 25 years for coupon specimens incubated at pH = 12. If the reaction rates remain constant, 50–60 years are required for a 50% loss in relative compressive strength of coupon specimens under the same conditions. The expected remaining resistances are relative to specimens incubated in water and ignore the effect of aging on the mechanical properties of polymers.

LIMITATIONS OF THIS 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 25-40 times larger in diameter than the tested specimens. Accordingly degradation of real piles is expected to occur over considerably longer duration. Second, specimens were punched out from the foamed core, whereas the material that surrounds the core is much denser and 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 mechanisms may become operative only at elevated temperatures and may be absent at lower temperatures.

The calculated remaining resistance in Fig. 13 are relative to the strength of specimens incubated in a neutral environment (pH=7) and ignore the effect of aging on the mechanical strength of the specimens.

CONCLUSIONS

Exposure to the acidic environment (pH =2) and alkaline environment (pH = 12) had a consistent measurable degradive effect on recycled HDPE, particularly at the highest incubation temperatures (55°C and 75°C). Incubation in acidic environment resulted in more degradation than alkaline environments.

Accelerated degradation by high temperature incubation resulted in an increase of control specimens incubated in a neutral environment. Therefore, the strength of the specimens incubated in acidic and alkaline environments were normalized by the strength of specimens incubated in the neutral environment, for the same incubation period

An estimated 25% loss in resistance at 10% strain, is projected to take 21 years for coupon specimens incubated at pH = 2 and 25 years for coupon specimens incubated at pH = 12. If the reaction rates remain constant, 50–60 years are required for a 50% loss in relative compressive strength of coupon specimens under the same conditions. These projected remaining resistances are relative to specimens incubated in water and ignore the effect of aging on the mechanical properties of polymers.

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LIST OF TABLES & FIGURES

Table 1 — Environmental Conditions of Reactors

Table 2 — Incubation Time vs. Characteristic Strength Values at 10 % strain

Fig. 1 — Assumed Distribution of Reaction Energys

Fig. 2 — The Arrhenius Model (i) Change In Measured Experimental Property with Time for Different Incubation Temperatures (ii) Derived Arrhenius Plot

Fig. 3 — Cross Section of Seapile™ (top) and Pile Core Showing the Location of Punched Specimens (bottom)

Fig. 4 — Schematic of Test Reactor

Fig. 5 — Density Distribution of Tested Specimens

Fig. 6 — Data Normalization (i) Conventional Stress Strain Curves (ii) Characteristic Strength vs. Strain Curves for the Conventional Stress Strain Curves Shown in (i).

Fig. 7 — Characteristic Strength vs. Strain Curves for Reactor No. 9 (pH = 2, Incubation Temperature = 75°C)

Fig. 8 — Increase in Characteristic Strength of Specimens Incubated in Neutral Environment with Time

Fig. 9 — Characteristic Strength of Specimens Incubated in Acidic Environment (pH =2) Normalized by Characteristic Strength of Specimens Incubated in Neutral Environment (pH =7) vs. Incubation Period

Fig. 10 — Characteristic Strength of Specimens Incubated in Acidic Environment (pH = 12) Normalized by Characteristic Strength of Specimens Incubated in Neutral Environment (pH =7) vs. Incubation Period

Fig. 11 — Arrhenius Plot for Different Remaining Strengths at 10% Strain (Acidic Environment, pH =2)

Fig. 12 — Arrhenius Plot for Different Remaining Strengths at 10% Strain (Alkaline Environment, pH =12)

Fig. 13 — Remaining Relative Resistance at 10% strain in Room Temperature

Table 1 — Environmental Conditions of Reactors

Reactor No.	Temperature	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

Table 2 — Incubation Time vs. Characteristic Strength Values at 10 % 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	7467.4	7467.4	7467.4	7467.4	7467.4	7467.4	7467.4	7467.4	7467.4
34	7186.4	7559.6	6710	5555.8	7986.5	8234.1	7507.3	7379.3	7860.2
63	7991.6	7973.3	6698.3	6701.8	7475.8	5876.1	6641.9	7281.6	8601.7
98	8945.5	9464.4	7461.3	8835.7	7971.8	9245.8	8911.6	9260.7	9757.6
127	8762.4	9625.6	6989.1	9156.1	9557.1	9167.2	9197.9	9170.6	9086.4
159	8676	9629.1	5681.3	8780.8	9530.4	8567.8	9311.1	8689.4	7362.9
196	8981.4	9006.2	6373.5	8194.9	9560.9	8508.3	8890.5	9521.6	7391.8
228	8812.3	8438	6771.4	7550.8	8837.8	9286.8	10134	9147.4	8110.8
262	8696.9	9652.6	5792.3	7711.8	9342.5	8835.9	9692.9	9357.1	8607
290	9572.5	9318.6	5643.3	7841.4	8906.9	9075.9	9641.1	8787.6	8758.4
320	9790.3	9411.6	6563	7676.9	9270.8	9820.2	9872.1	9415.7	8555.6
354	9333.4	7599.2	6593.7	7917.3	10337	9139.8	9801.6	9084.3	8376.5
385	9721.4	6837.3	5972.2	7254	9695.9	8659.2	9808.8	9016.7	7968.4

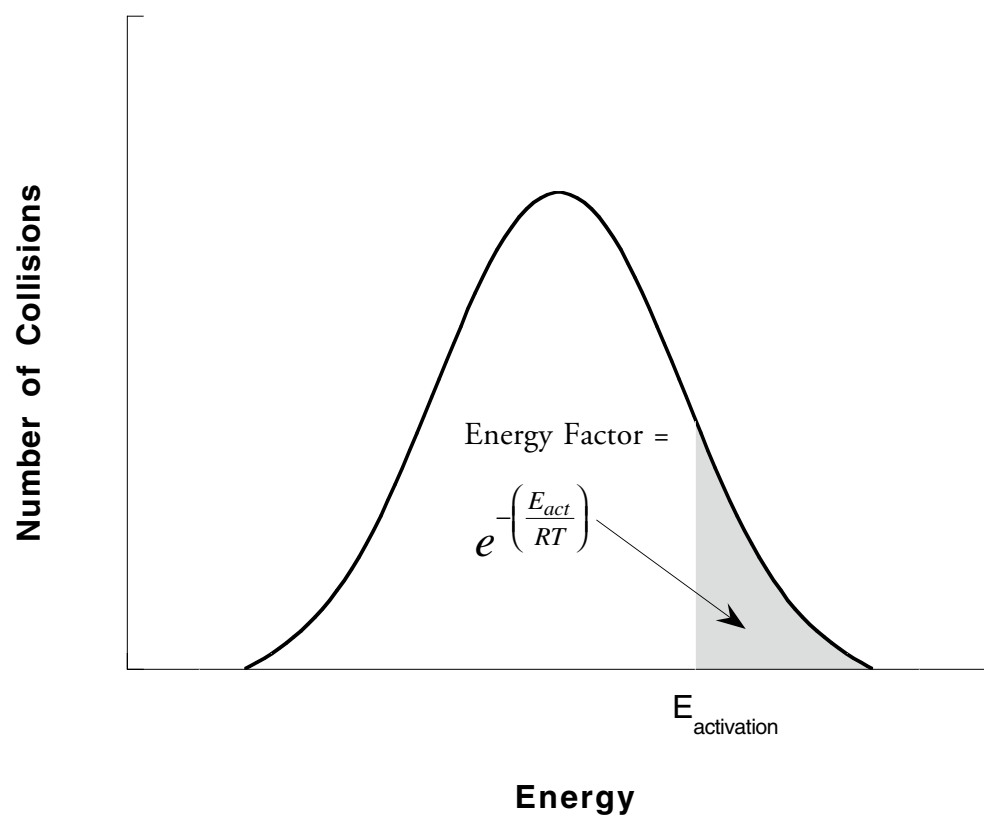


Fig. 1 — Assumed Distribution of Reaction Energys

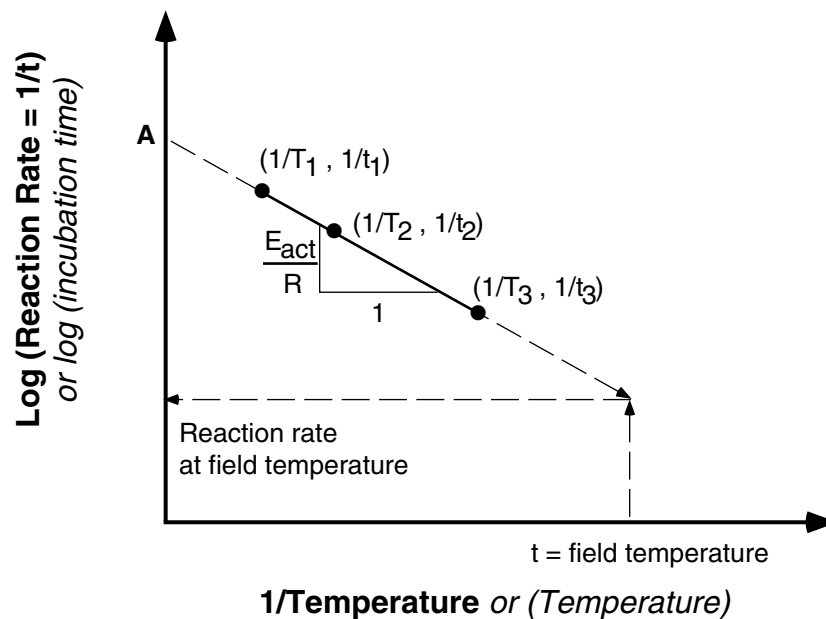
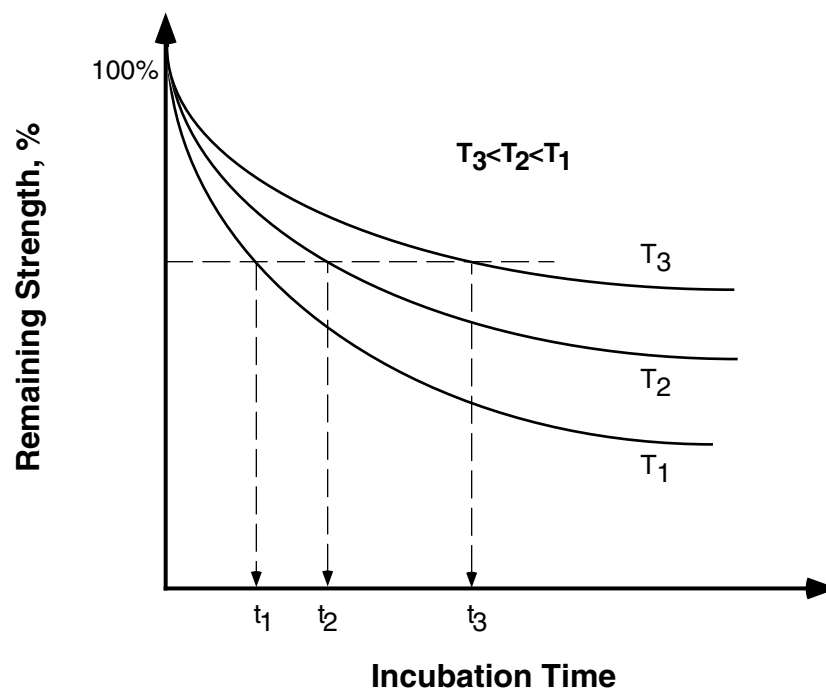


Fig. 2 — The Arrhenius Model (i) Change In Measured Experimental Property with Time for Different Incubation Temperatures (ii) Derived Arrhenius Plot

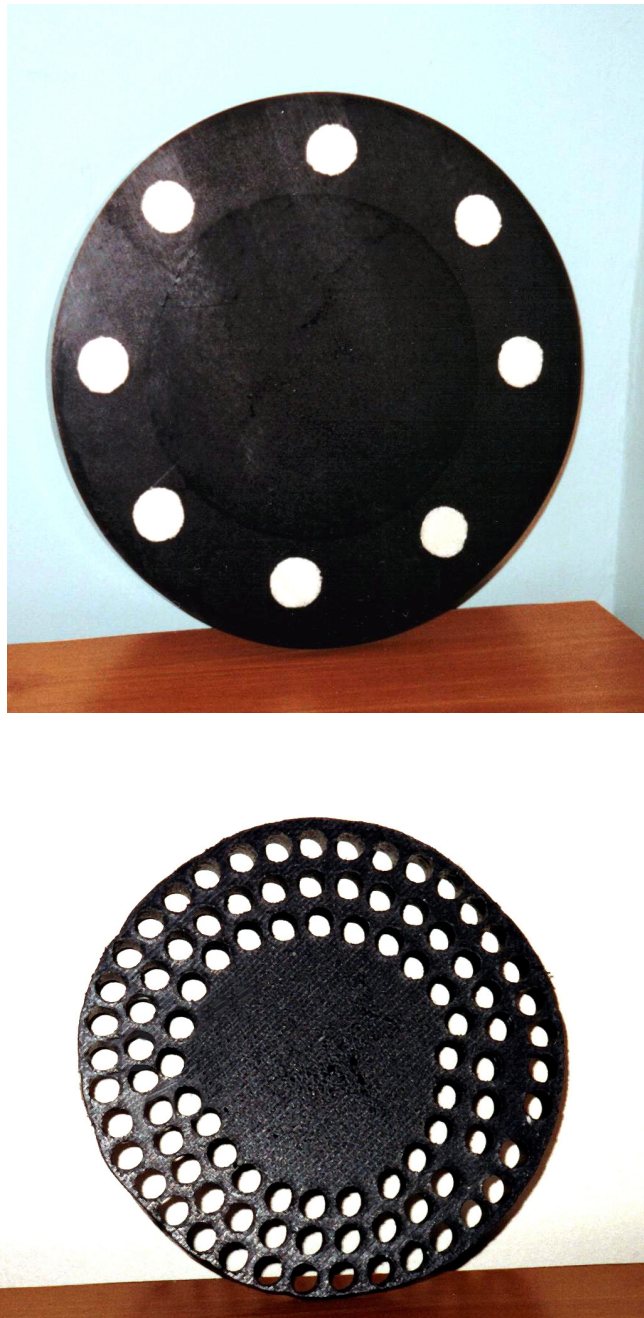


Fig. 3 — Cross Section of Seapile™ (top) and Pile Core Showing the Location of Punched Specimens (bottom)

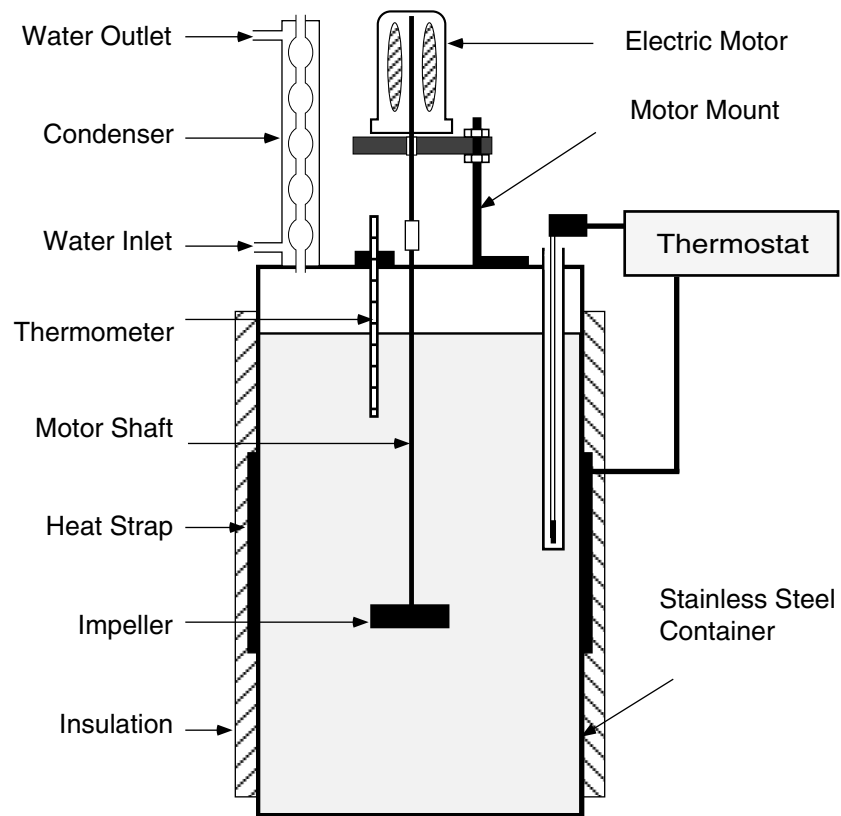


Fig. 4 — Schematic of Test Reactor

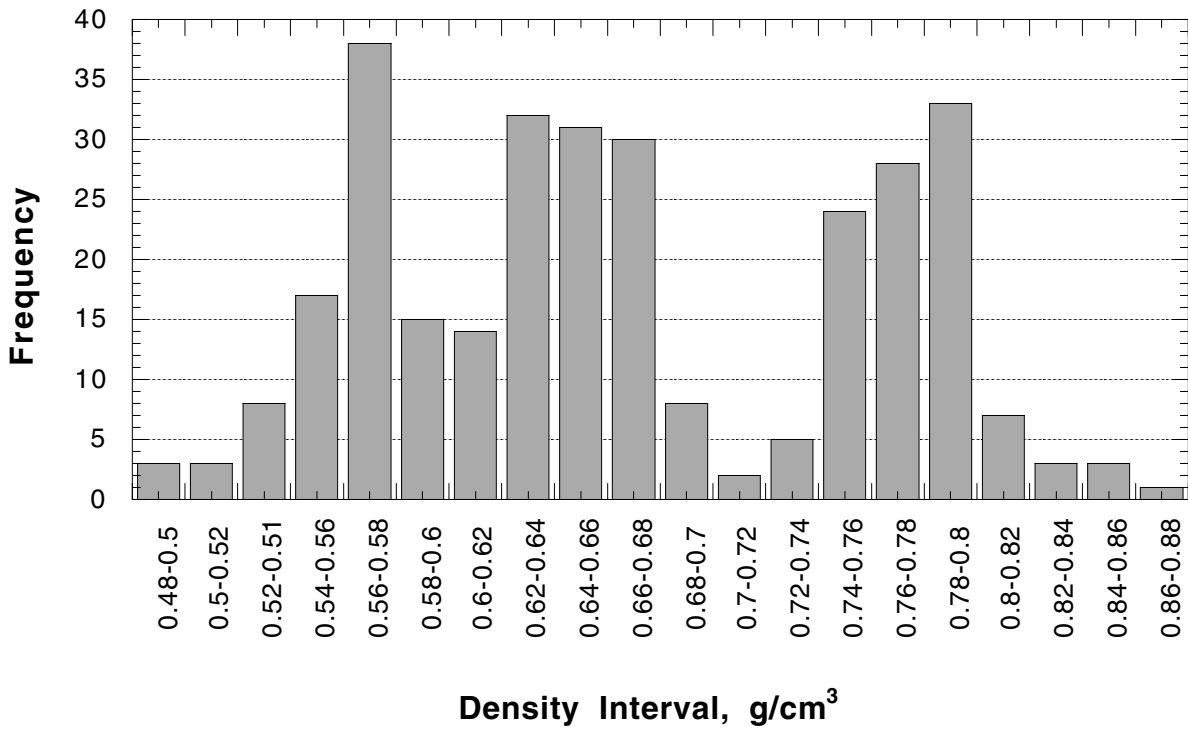


Fig. 5 — Density Distribution of Tested Specimens

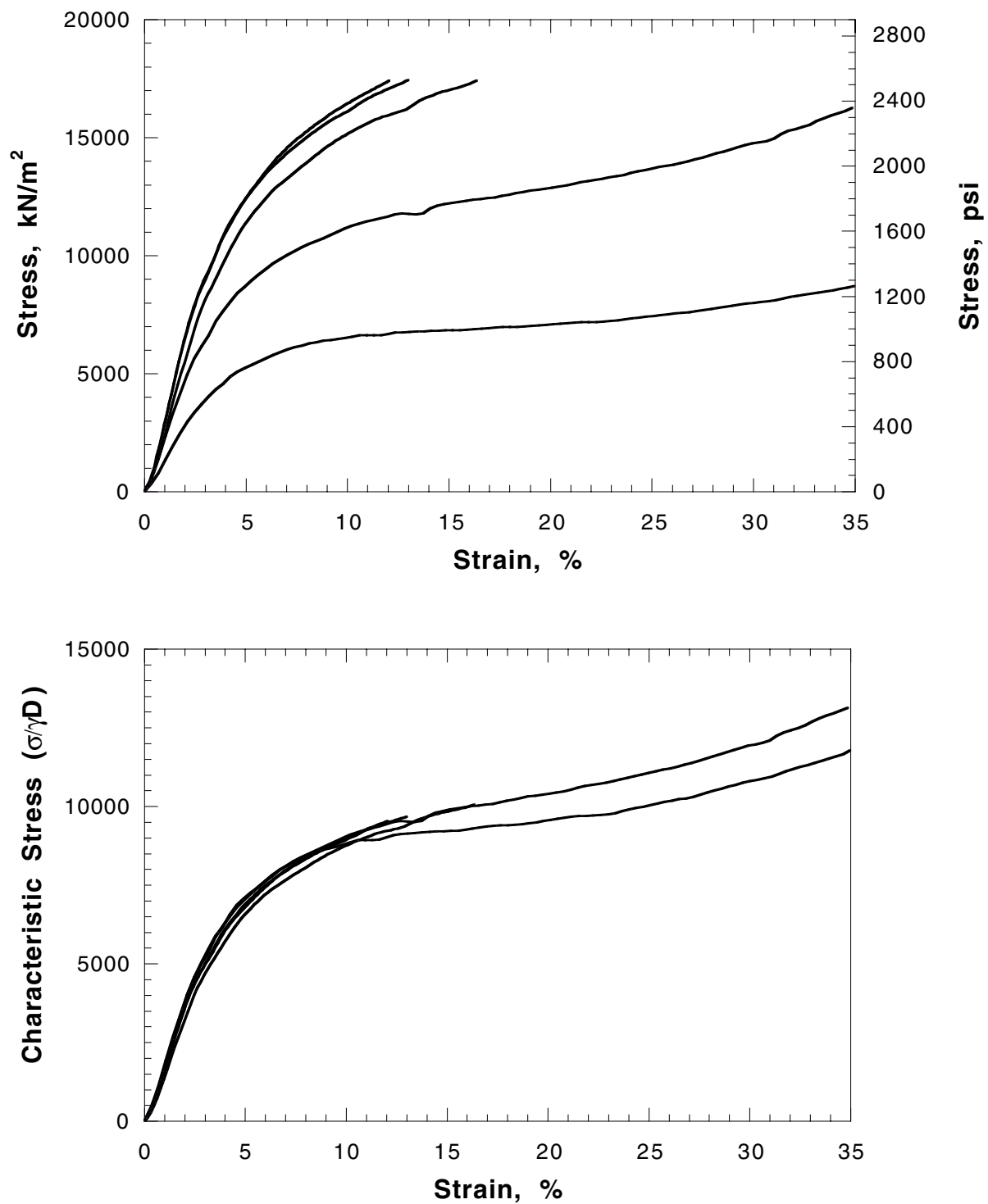


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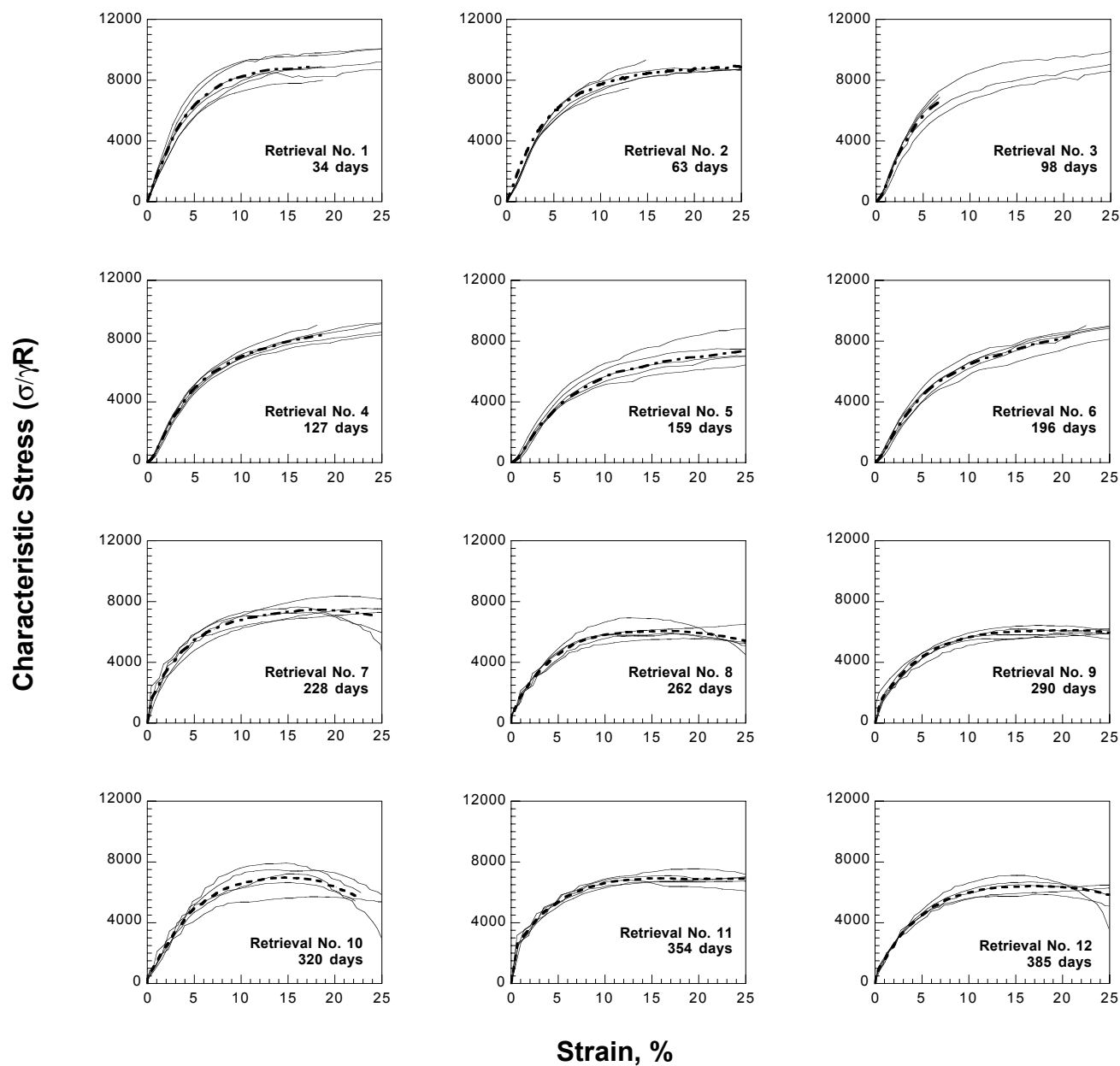


Fig. 7 — Characteristic Strength vs. Strain Curves for Reactor No. 9
(pH = 2, Incubation Temperature = 75°C)

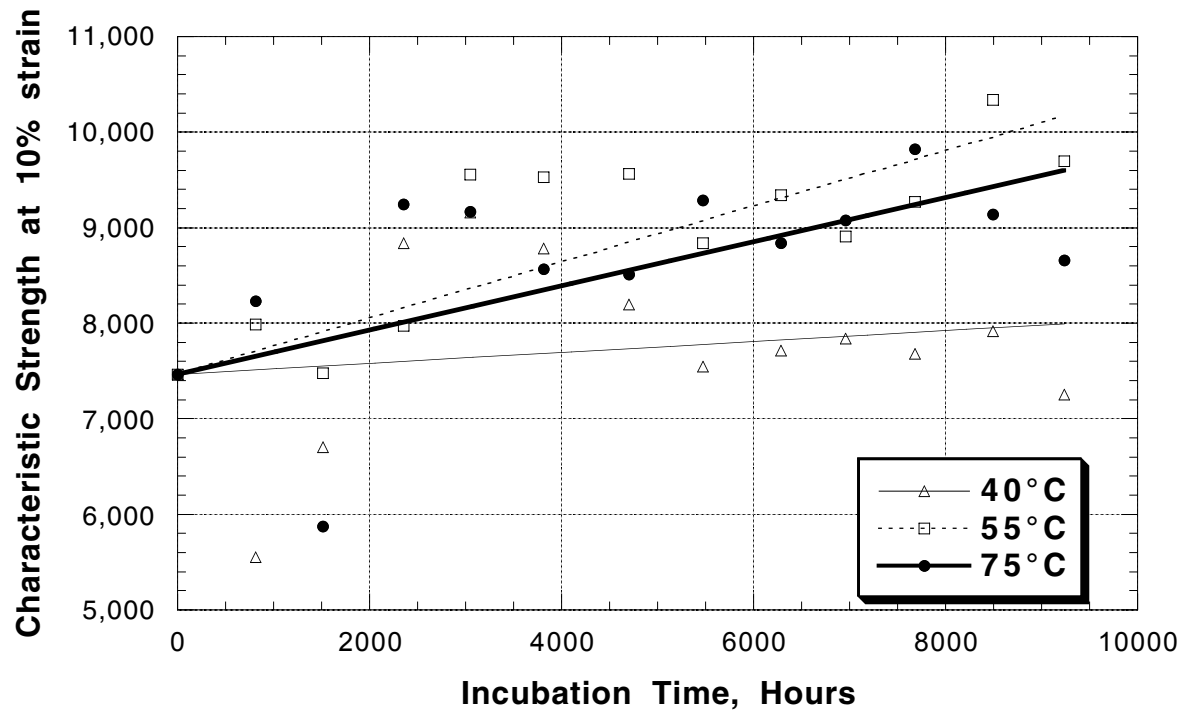
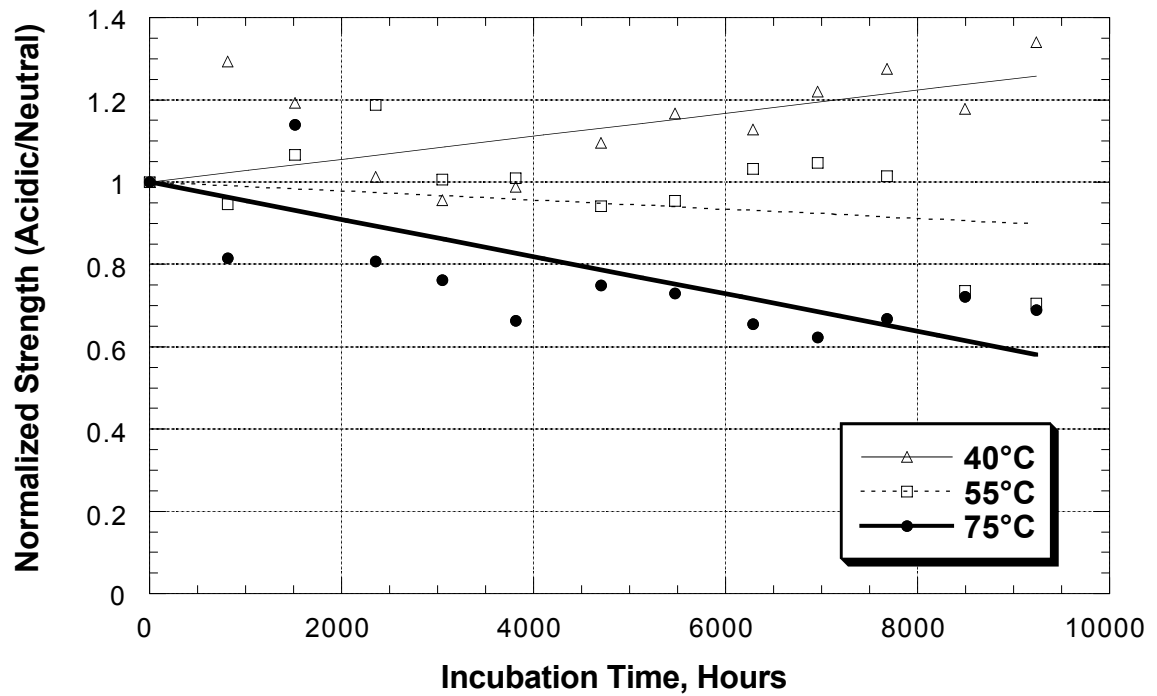
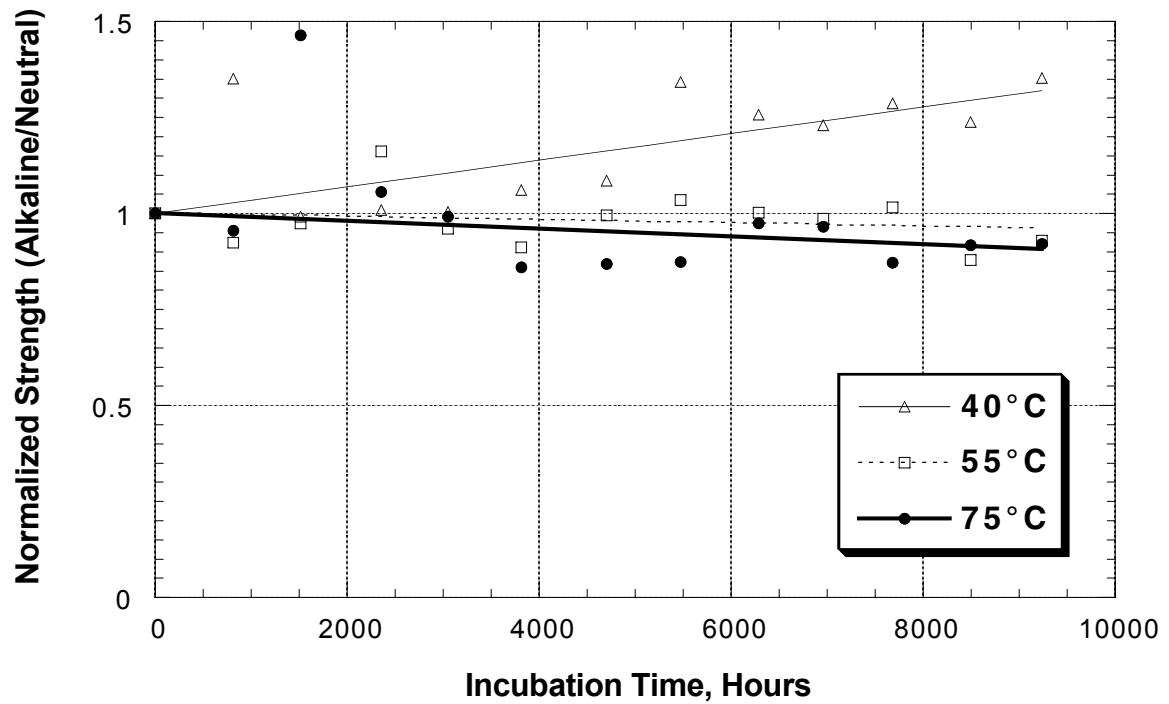


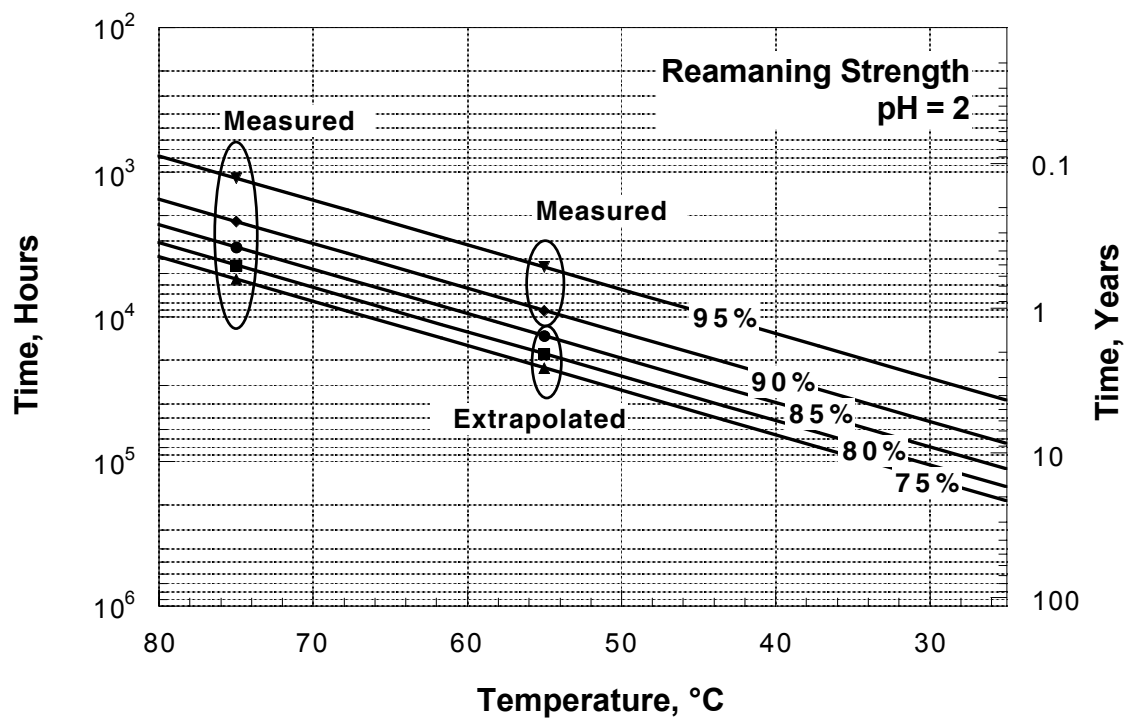
Fig. 8 — Increase in Characteristic Strength of Specimens Incubated in Neutral Environment with Time



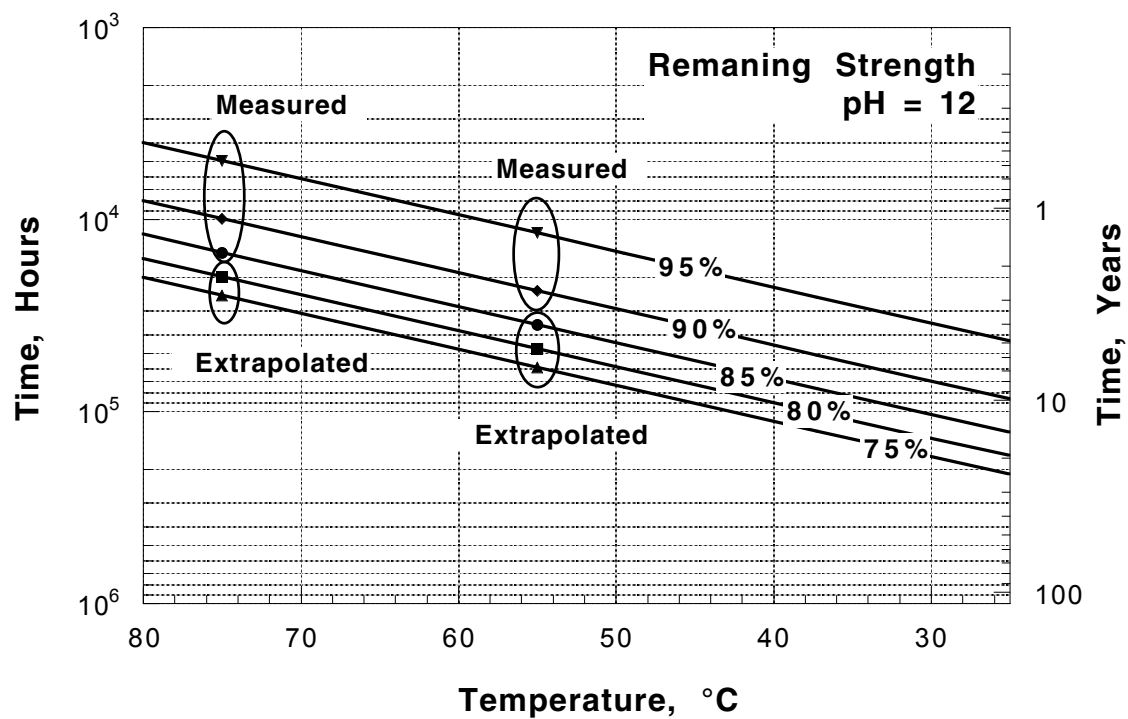
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Normalized by Characteristic Strength of Specimens Incubated in Neutral Environment
(pH =7) vs. Incubation Period**



**Fig. 10 — Characteristic Strength of Specimens Incubated in Acidic Environment (pH = 12)
Normalized by Characteristic Strength of Specimens Incubated in Neutral Environment
(pH =7) vs. Incubation Period**



**Fig. 11 — Arrhenius Plot for Different Remaining Strengths at 10% Strain
(Acidic Environment, pH=2)**



**Fig. 12 — Arrhenius Plot for Different Remaining Strengths at 10% Strain
(Alkaline Environment, pH =12)**

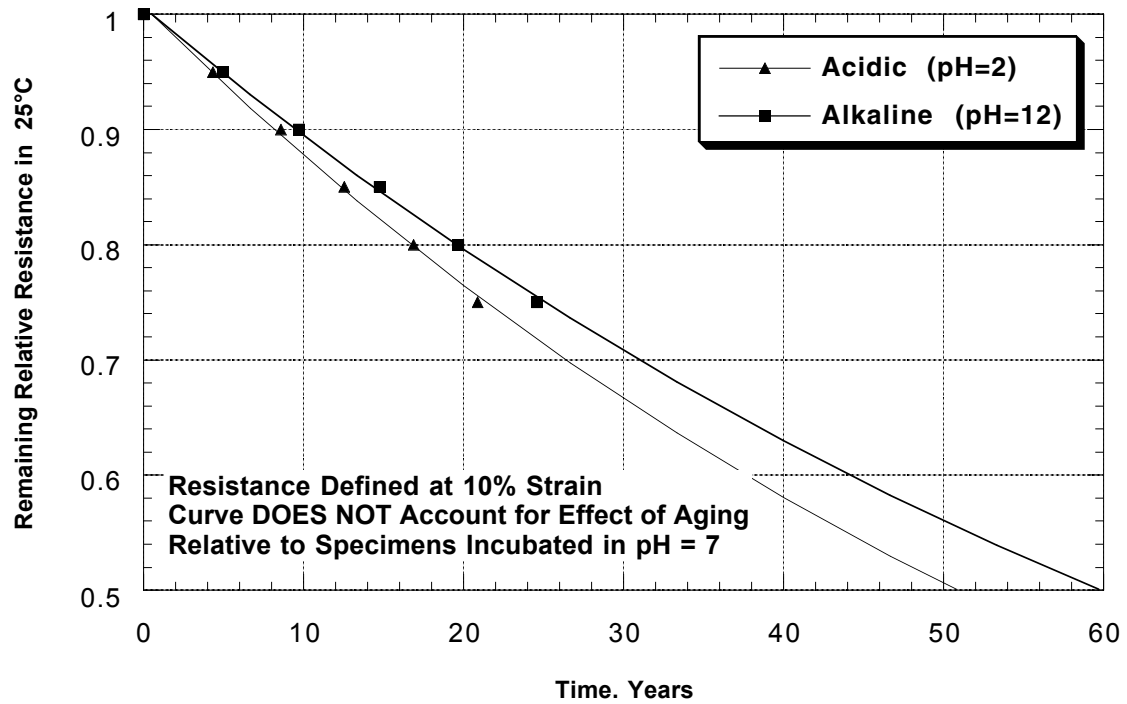


Fig. 13 — Remaining Relative Resistance at 10% strain in Room Temperature