

# **Durability of Recycled Plastic Piles in Aggressive Soils**

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## **ABSTRACT**

### **DURABILITY OF RECYCLED PLASTIC PILES IN AGGRESSIVE SOILS**

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In the United States millions of piles are used to support residential, commercial, and transportation structures. There are, however, some problems associated with the use of traditional piling. It is now more commonly required to install piles on corrosive and contaminated soils, due to industrialization. The durability of concrete, corrosion of steel, and deterioration of wood is a serious hindrance to construction in these environments, particularly where high concentrations of sulfides or chlorides are present.

The objective of this project is to assess the durability of piling made of recycled plastics in aggressive soils for long term usage in civil infrastructure application. This required the development of acceleration tests permitting prediction of the behavior of the plastic piles in actual use, within the short duration of this project.

The scope of this research is limited to the laboratory investigation of the accelerated degradation of specimens of Seapile™, which is manufactured by Seaward International. The experimental program is intended as an empirical investigation of the effects of specific environmental variables on the degradation process, in order to estimate the product's service life.

In order to facilitate testing, specimens are exposed to solution with fixed acidic, basic & neutral liquids at elevated temperature. An Arrhenius model is used to quantify the degradation of the specimen & predict the service life of the product.

Arrhenius model estimates are based on results obtained under conditions of intensive stirring of aqueous media which intensifies the degradation action. Therefore, all calculations of strength loss should be considered as a conservative estimate for the degradation rate for in-use condition.

Only the acidic environment had a considerable degradation effect on the Seapile™ samples. At this severe acidic environment (pH=2) an estimated 25% loss in resistance at 1% strain, of the coupon specimens extracted from Seapile cores takes place in about 14 years. The half-life (50% loss) is estimated to occur in 33 years. Larger diameters of plastic piles as compared to the 1/2" coupon specimens may result in delay of the degradation process, which may be caused by diffusion.

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# Chapter One

## INTRODUCTION

### 1.1 WHY PLASTIC PILES?

In the United States millions of: piles are used to support residential, commercial, and transportation structures. There are, however, some problems associated with the use of traditional piling. It is now more commonly required to install piles in corrosive and contaminated soils, due to industrialization. The durability of concrete, corrosion of steel, and deterioration of wood is a serious hindrance to construction in these environments, particularly where high concentrations of sulfides or chlorides are present (Iskander & Hassan 1998). The deterioration of timber, concrete, and steel piling Systems costs the United States nearly \$1 billion per year for repair and replacement (Lampo 1996). Composite materials such as fiber-reinforced polymers (FRP) can offer performance advantages when compared to steel, concrete, or timber. These materials can be designed to perform according to the required specifications for piling in adverse environments. Their inherent performance advantages include corrosion resistance, high oriented strength structural shapes, durability, and low maintenance. In addition to performance advantages, the use of composites in aggressive environments appears to be more economical when life-cycle costs are considered.

## **1.2 ENVIRONMENTAL CONCERNS**

In the case of marine piling, the federal Water Pollution Control Act of 1972 gradually rejuvenated many of the nation's waterways and harbors. With the return of the marine life, tiny marine borers started attacking the untreated timber piles that support many of the nation's harbor piers. In some states, it is not permissible to replace the piling with creosote-treated timber, since the use of creosote poses a threat to marine life and violates some states and federal guidelines, particularly when large numbers of piles are involved.

At the same time, over 3.8 billion kg of rigid plastic containers are produced annually in the United States (Lampo 1995). Most of these containers are made of high-density polyethylene (HDPE) milk jugs, and polyethylene terephthalate soda bottles (McLaren 1995). As much as 3.3 billion kg of these materials is landfilled, and the rest is recycled (Modern Plastics 1997). The use of recycled plastics to manufacture composite piling products is advantageous, because it can utilize plastics that would have been otherwise landfilled.

## **1.3 CURRENT APPLICATIONS**

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. The majority of the piles produced by the industry today have comparable properties to wood products. Most composite piling products are made of fiberglass or HDPE with fiberglass reinforcement and additives to improve their mechanical properties, durability, and ultraviolet (UV) protection. These pile products are often nonhomogeneous and exhibit anisotropic viscoelastic behavior.

Polymer-based resins are heavier than wood and sometimes foaming of the resin is used to make the product lighter. The composite resin formulation is a complex process that involves optimizing cost and material properties to achieve the desired material performance.

## **1.4 RESEARCH CHALLENGES**

The plastic composite industry and the rapidly emerging industry of recycled plastics have made substantial research and development investment to develop high performance composite construction materials. However, the developed materials suffer from several disadvantages as follows:

1. At this time, composite materials, depending on location, cost approximately two or three times the cost of creosote treated timber piles. However, manufacturers claim that composite piling costs less to maintain, lasts twice as long as treated timber piling, and does not present an environmental disposal problem.
2. Composite piling is less efficient to drive than conventional piling materials.
3. The long-term performance of composite materials under increasingly larger structural loads is not well defined.
4. Because of their low modulus, composite piling materials may exhibit large deformations in excess of the settlement permitted by building codes.

The existing composite piling materials are the first generation of composites in foundation engineering. Composite materials faced similar difficulties in other fields of engineering; however, these difficulties were overcome in later generation products (Reich 1996). Similarly, it is expected that manufacturers of composite piling products will eventually overcome the current disadvantages, and composite piling will gain wider use, with time, in foundation engineering applications.

## **1.5 OBJECTIVES & SCOPE OF THIS RESEARCH**

The objective of this project is to assess the durability of piling made of recycled plastics in aggressive soils for long term usage in civil infrastructure application. This requires the development of accelerated tests permitting prediction of the behavior of the plastic piles in actual use, within the short duration of this project.

The scope of this research is limited to the laboratory investigation of the accelerated degradation of specimens of Seapile™ which is manufactured by Seaward International. The experimental program is intended as an empirical investigation of the effects of specific environmental variables on the degradation process, in order to estimate the product's service life.

In order to facilitate testing, specimens are exposed to solution with fixed acidic, basic & neutral liquids at elevated temperature. An Arrhenius model is used to quantify the degradation of the specimen & predict the service life of the product.

# Chapter Two

## STATE OF THE PRACTICE

### 2.1 HISTORICAL BACKGROUND

In April 1987 the first prototype recycled plastic piles was driven at The Port of Los Angeles (Horeczko 1995). The pile consisted of a segmented, 18 m (60 ft) long, 33 cm (13 in.) diameter recycled plastic, with a 12.5 cm (5 in.) diameter steel pipe core. Each 6 m (20 ft) segment was connected by a threaded coupling. Experience, however, has shown that steel core composite piling suffered from core delamination, due to thermal stresses. Over the next few years, several vendors produced a variety of piling products made of virgin, recycled, and hybrid composites. The main polymers currently in use in plastic piling include fiberglass and HDPE combined with stabilizers and fiberglass reinforcement.

Composite piles were installed in a number of demonstration projects in the New York Metropolitan area. For example, Tiffany Street Pier was constructed entirely from recycled plastics (Grobler 1996a; Wright 1995). The pier was struck by lightning, which severely damaged the superstructure, leaving only the composite piling and thicker girders (Grobler 1996b; “Plastic” 1996). Three different pile types were also installed in Port Elizabeth in a research project sponsored in part by the U.S. Army Corps of Engineers and a consortium of composite pile manufacturers represented by The Composite Institute. These tests were conducted to study the feasibility of using composite piles as a fendering system to replace timber piles.

Two of the composite piles installed in Port Elizabeth were made of recycled plastics and reinforced with fiberglass (structural rebars and randomly distributed fibers). The third pile was made of pultruded FRP composite structural section, and covered near the top with a recycled-plastic pipe section, and plastic-lumber inserts. Timber piles were also installed as reference piles for comparison.

Composite piles were also used in a number of military and civilian projects (Busel 1995). For example, composite piling was installed in a number of military facilities in Hueneme, Calif., San Diego, Calif., and New Orleans, La. Composite piles were also installed in a number of ports and waterfront facilities such as Los Angeles, Calif., El Sauzal, Mexico; St. Petersburg, Fla., Newark N.J., and in Lewes, Del.

## **2.2 AVAILABLE PRODUCTS**

In late 1998, a number of manufacturers were marketing composite piling products. Although many manufacturers advertise that their product can be used for bearing and structural applications, so far most of these products have been used in fendering applications only. The products available in the market today can be classified into the following types.

### 2.2.1 Steel Pipe Core Piling

Steel core piling was the first plastic piling product in the American market. The piles consist of a recycled plastic shell encasing a steel pipe core (Fig. 2-1) The steel pipe core provides all of the structural strength (Plastic Piling 1995). Plastic Piling Inc. is currently the only manufacturer of this type of piling. Piles are available in 20-60 cm (8-24 in.) outer diameter and up to 23 m (75 ft) long. The structural pipe cores range from 10-40 cm (4-16 in.) outer diameter, with wall thickness ranging between 6 and 40 mm (0.237 and 1.594 in.) (Engineering 1997). In the past these piles were produced in 6m (20 ft) segmental section that were connected together



Fig. 2-1 Steel Pipe Core Piling.

with threaded coupling (Horeczko 1995). Early versions of this product suffered from delamination of the steel core from the plastic shell due to the difference in thermal coefficients of expansion. However, the manufacturer is currently producing products that are guaranteed against shrinkage and expansion cracking for a period of: five years. These piles were first used in April 1987 at Berth 120 in the port of Los Angeles. More recently, steel core piling has been used in Pier 16 at



the U.S. Naval Amphibious base in San Diego and in Terminal Porturia in El Sauzal, Mexico (Engineering 1997).

### 2.2.2 Structurally Reinforced Plastic Matrix

These piles typically consist of a recycled plastic matrix reinforced with fiberglass or steel rods (Fig. 2-2). Typically, the plastic matrix is chemically treated with

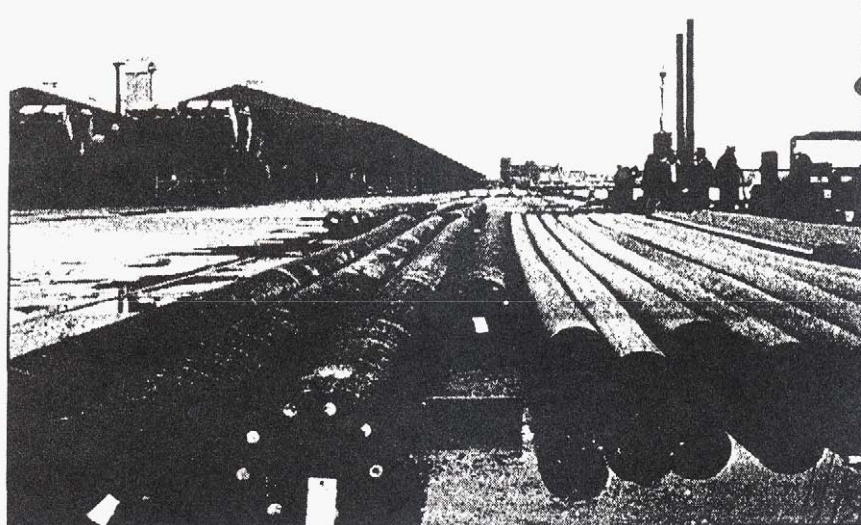


Fig. 2-2 Structurally Reinforced Matrix Piling on Left and Fiber Reinforced Plastic Piling on Right.

antioxidants and ultraviolet inhibitors to retard the effects of UV light on the plastic. When reinforced with fiberglass, piling is nonmagnetic and recyclable. Seaward International, Inc. and Plastic Piling Inc. produce piles of this type; piles are available in 25-40 cm (10-16 in.) diameters and are reinforced with 6-16 fiberglass-reinforcing bars ranging in diameters between 25 and 36 mm (1-1.41 in.) (Engineering 1997 and “Seapile” 1994), Seapile™, which is a product of Seaward International, Inc., uses approximately 800 recycled 1-gal. milk jugs per linear meter. Seapile is produced by a continuous extrusion process that is said to allow the manufacturer to

produce piles of any length (Taylor 1995). Seapile is currently being used by naval facilities for fendering applications, and is being pilot tested for bearing loads up to 10 t (Lindsay 1996) and in the Tiffany Pier Project.

### 2.2.3 Fiberglass Pipe Pile

Fiberglass pipe piles typically consist of an acrylic-coated fiberglass tubular section. The fiberglass (glass/vinyl ester) shell provides structural strength, and the acrylic coating protects the pile against abrasion, UV, and chemical attacks ("Hardcore" 1997). Hardcore Dupont and Lancaster Composites produce piles of this type under the commercial names FTP and CP40, respectively. Hardcore piles are typically filled with concrete after installation to improve their structural performance. Lancaster Composites CP40 piles are filled with concrete and cured, prior to driving (Stapleman 1997). Hardcore uses a process called vacuum resin transfer molding (resin infusion) while Lancaster Composites uses filament wound tubes. Piles are available in 20-45 cm (8-18 in.) diameters, with 4.6-9.1 mm (0.18-0.36 in.) wall thickness, in any shippable

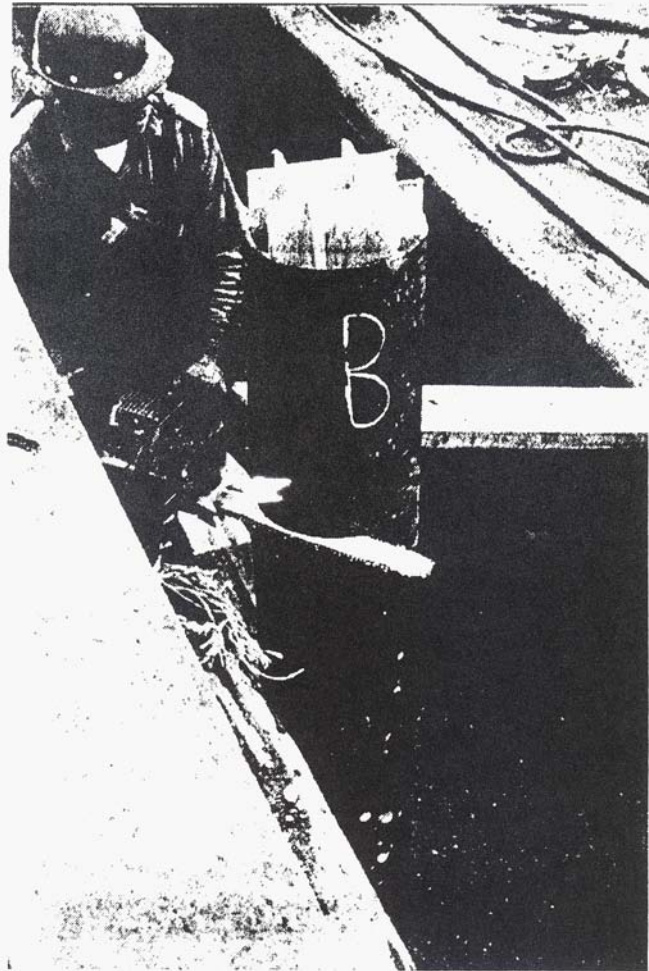


Fig. 2-3 Fiberglass-Pultruded Piling.

length. Hardcore piles are currently being used by the U S Army Corps of Engineers facility in New Orleans and by the Bay Authority Pier End Project at Delaware River (Phair 1996).

#### **2.2.4 Fiberglass-Pultruded Piling**

Creative Pultrusions ("High" 1997) produces a piling product comprised of a pultruded fiberglass cross section (glass/vinyl ester) that resembles a tic-tac-toe pattern (Fig. 2-3). The pattern consists of two sets of orthogonal fiberglass plates joined at four intersecting points. When the pile is used as a fender, its top portion is encased by a 35 cm (14 in.) diameter HDPE shell, and the tic-tac-toe pattern is filled with HDPE inserts. The shell and inserts are used to protect the fiberglass, help absorb ship impact, and connect fendering fittings. This pile was used in 1996 in a demonstration project at Berth 7 in Port Newark, N.J. and in the Tiffany Pier Project.

#### **2.2.5 Fiber Reinforced Plastic Piling**

Fiber reinforced plastic piling consists of a recycled plastic matrix with randomly distributed fiberglass reinforcement in the matrix. Trimax is currently the only manufacturer of this product and produces a variety of structural members that conform to lumber industry standards. Trimax lumber consists of 20% glass-fiber-reinforced, high density extruded recycled polyethylene. The product consists of an outer solid section with a foamed center (Fig. 2-2). Piling is available in 25 cm (10 in.) diameter with a standard length of 7.5 m (24 ft), but longer length could be custom made in any transportable length. Trimax lumber was used in the construction of the Tiffany Street Pier in New York City.

## **2.3 ENGINEERING PERFORMANCE**

### **2.3.1 Drivability**

Composite materials present a number of difficulties related to pile driving. Composites have high damping coefficients and low stiffness and are therefore less efficient to drive than traditional materials such as steel, concrete, and timber. Reinforcing cores made of steel have been used in the past to enhance the drivability of composite materials; however, delamination of the core has been reported in some cases. When a reinforcing core is used, a driving plate is required, because the plastic and steel react differently to the hammer blows (Heinz 1993). Some of the early piles driven in Los Angeles developed separation of the plastic from the pipe core as the pipe core drove up into the timber cushion block of the hammer system (Heinz 1991). Precast concrete fiberglass pipe piles drive easier than other composite pile types due to their high stiffness and low clamping coefficients.

A second problem related to driving composite materials is their anisotropy and nonhomogeneity that may result in localized areas of lower strength, particularly when recycled plastics are used. Accordingly, the integrity of the piles may be compromised during driving or transport. So far composite piling has been installed using lightweight hammers that drive the whole cross section. Alternative driving methods such as driving hollow piles using a mandrill similar to that used for step-taper piles may provide a more efficient approach to installation of composite piling.

### **2.3.2 Soil-Pile Interaction**

A number of differences exist between composite piling and conventional piling materials that affect load transfer behavior. First, composite materials have a low stiffness that may result in large viscoelastic compressions that may cause differential settlement and may adversely affect the performance of the structure. Second, the composite pile modulus is both time and load dependent. Of particular interest is the effect of creep on load transfer, and the possibility of time-dependent load shedding. Additionally the interface between FRP composites and granular materials depend on the relative surface roughness, the normal stress level, the initial density of the soil mass, and the angularity of particles, which may result in partial slippage along the pile shaft during loading (Han 1997). Further research is needed to characterize most of these effects.

The creep behavior of plastics should not necessarily be cited as a cause for rejecting composite piling, but it is an important factor that must be considered in its use. Wood, steel, and concrete all creep, and designers limit their service stresses to a magnitude that effectively controls creep. Likewise, stresses in plastic and composite materials should be maintained at low levels, if the applied load is maintained for a long time.

### **2.3.3 Structural Behavior**

FRP composite piling is an engineered product with predictable strength and stiffness properties. Timber on the other hand is a natural product with random variations in its properties. When FRP composites are used to replace timber piling, a better definition of performance can be achieved if appropriate quality control

measures are implemented. However, so far most of the available products are made of recycled plastics & have a high degree of variability in their properties.

Polymers are viscoelastic, which influences the behavior in two ways. First, viscoelasticity causes creep. Second, the more rapidly the load is applied, the stronger and stiffer the material behaves.



**Fig. 2-4** Handling Fiber Reinforced Plastic Piling; Low Stiffness of some Composite Piling Materials.

FRP composites usually have low stiffness, which can be advantageous in a number of situations. First, concrete and steel piles are considered too stiff for fendering application, thus making plastics an ideal potential choice. Second, composites can dampen seismic forces transferred to the structure through the foundations. Third, composite piling may reduce moments in piled rafts. However, for a few pile types, such as fiber reinforced plastic piling, low stiffness may cause problems during installation and handling (Fig. 2-4).

#### **2.3.4 Durability**

Polymers have been successfully used in soil for the last 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. Even so degradation of buried plastics in certain corrosive soil environments has been reported. Certain soil environments can contain significant amounts of chemicals identified as degradative or corrosive to polymers. However, these environments are characterized by extreme acidic conditions, such as sulfate soils (pH 1-2) or extreme alkaline conditions (pH 9-12) (Salman et al. 1997a).

#### **2.3.5 Environmental Impact**

FRP composite piles offer unique solutions in some environments. For example, the federal Water Pollution Control Act of 1972 has gradually led to the rejuvenation of the New York Harbor's marine environment. With the return of marine life to the harbor, tiny marine borers such as the *Teredo Novalis* and *Bankia Gouldi* returned (Grobler 1996a; Wright 1995). Many of the harbor piers are supported by untreated timber piles and are becoming vulnerable to marine borers' attacks. In some areas marine borers have consumed up to 90% of untreated wood piling in as little as 12 months (March 1996). Concrete and steel piles are considered too stiff for fendering application, thus making plastics an ideal potential choice. Composite piling offers a number of environmental advantages over conventional creosote-treated timber piling, as follows:

Creosote and CCA treated timber presents a growing environmental disposal problem. Creosote is listed as a toxin by the Environmental Protection Agency (Article U0061, RCRA).

The toxic chemicals used in pressure treatment of timber may pose a threat to marine life, particularly when used in large quantities.

Workers who handle creosote and CCA treated timber during manufacturing and installations are exposed to hazardous materials and have complained about potential health risks (Heinz 1993).

Wood products are becoming increasingly more expensive and difficult to obtain, particularly as regulations to protect old growth forests and the habitat of the spotted owl were enacted (March 1996).

Use of recycled plastics in FRP composite piling offers a solution to the mountains of solid plastic waste that are consuming valuable landfill space all over the United States.



# Chapter Three

## ENGINEERING PROPERTIES OF POLYMERS

### 3.1 BACKGROUND

Plastics are defined as, "Any of numerous organic, synthetic, or processed materials that are high molecular weight polymers", (Regal Plastics HandBook). A polymer is a product resulting from a chemical change involving the successive addition of a large number of relatively small molecules (monomer) to form the polymer, and whose molecular weight is usually a multiple of that of the original substance, (Regal Plastics HandBook).

Polymers are a tribute to man's creativity and inventiveness. They are truly man-made materials. Like any other material, they have their origins in nature, in such basic chemical elements as Carbon, Oxygen, Hydrogen, Nitrogen, Chlorine, and Sulfur. These elements in turn are extracted from air, water, gas, oil, coal, or even plant life. The possibilities of combining chemical elements to create plastics with different properties are almost endless. It is this diversity that has made plastics so applicable to such a broad range of endless uses and products today

From these basic sources come the feedstock of the so called monomers. The monomer as referred above is subjected to a chemical reaction known as polymerization that causes the small molecules to link together into ever-increasing longer chain of molecules. Chemically, the polymerization reaction converts the

monomer into a polymer, with a very high molecular weight, which is also called a plastic resin. The polymer or plastic resin must next be prepared for use by the processor, which will turn it into a finished product. In some instances, it is possible to use the plastic resin as it comes out of the polymerization reaction. More often, however, it goes through other steps that put it into a form that can be more easily handled by the processor and more easily run through processing equipment. The more popular forms of resins for processing are as pellets, granules, flakes, or Powder.

At the processor, these solids are generally subjected to heat and pressure, melted, adding special additives to provide the product with specific properties, then forced into the desired shape, such as sheets, tubes, or piles. At this stage reinforcement using fiberglass rods could be introduced, where the melted product is formed around the reinforcement elements.

The production process given above, shows how final plastic product can be obtained from virgin resins. There is also another method for obtaining plastics through the recycling process which has a very great impact on the environment. The manufacturer of recycled plastic lumber begins with the collection of raw materials, from the recycling program. After collection, the plastic is cleaned and pulverized. The resulting "confetti" arrives at the production site (plant) where it is melted in an extrusion machine. The machine ejects the molten plastic through a series of dies, which shapes the material as it cools. Recycled plastics products could also be reinforced by introducing fiberglass rods during, the extrusion process. Additives could also be added during the melting process to gain the. needed properties.

### 3.2 STATES OF BEHAVIOR

In this brief overview, different types of polymer behavior will be discussed. Plastic is inherently temperature dependent. At low temperatures it is strong and brittle. With increased temperature it becomes weaker and more ductile. There is

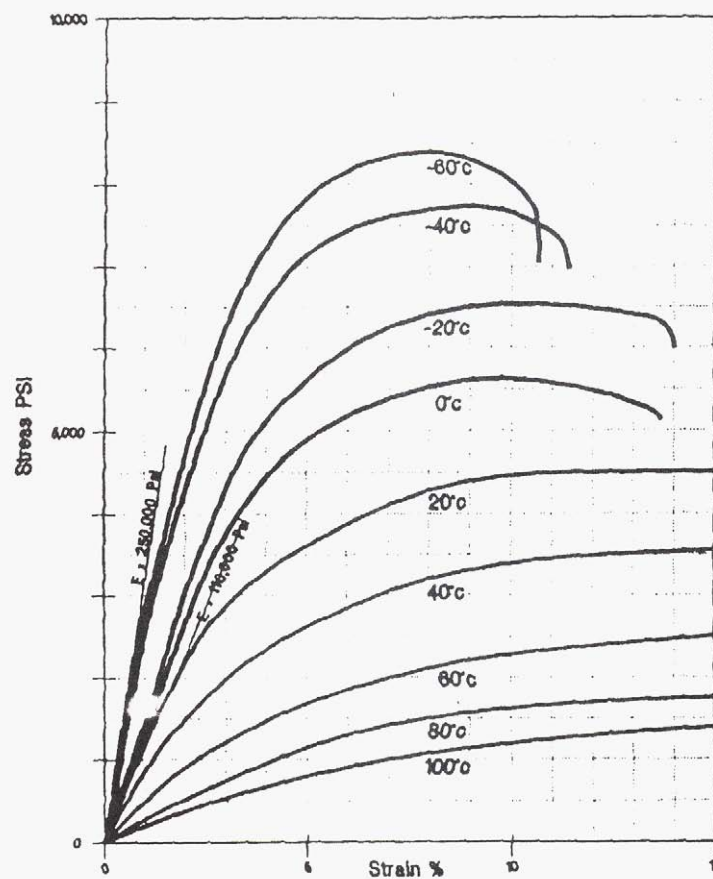


Fig. 3-1 Tensile Strength for High Density Polyethylene.

considerable behavioral difference in the temperature range of civil engineering structures, which might use the material. Fig 3-1 shows graphically the effect of temperature on the strength and ductility for High-Density Polyethylene (HDPE).

It is important to note that calling a polymer a "rubber" refers to a state, not to a type of material. Consider a deformation such as tensile, say 30 sec after an uni-axial load was imposed upon a specimen. That is, studying a time dependent young's modulus, usually called the tensile relaxation modulus defined as,

$$E(t) = \frac{\sigma(t)}{\epsilon}$$

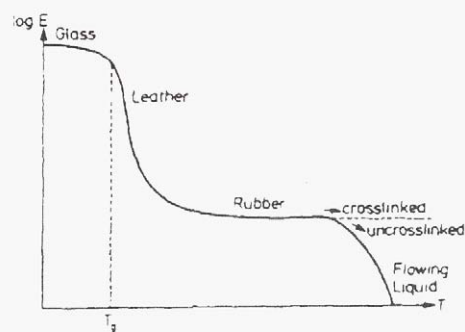
Where  $\sigma$  = stress at a given time and  $\epsilon$  = corresponding strain

Specifically for the time  $t=30\text{sec}$ , taking a number of identical specimens at various temperature  $T$ , one can construct curve of the tensile modulus  $E(30\text{sec}, T)$ .

Since  $E$  can change by several orders of magnitude it is usually convenient to work with  $\log E$ . Of-course 30sec. is only an example, but it is important that the same time pertains to all temperatures.

A typical curve of this kind for an elastomeric material is shown in Fig. 3-2. At low temperature the material is a "glass": the modulus is respectively high, fracture when it occurs is brittle. Then from the glass transition temp  $T_g$  up to, approximately,  $T_g+30\text{K}$  lies the leathery state with retarded high elasticity. A further temperature increase produces a further increase in the free volume,  $V_f$ , in the material, that is more space for polymer chains and their parts to move. From the region of retarded high elasticity the plastic material goes to instantaneous high elasticity in the rubbery state-characterized by the plateau of the curve. Now, two possibilities exist.

If the material is cross-linked and the temperature continued to increase, there is no significant change; the plateau persists. By contrast, if the cross-linking is absent, higher  $T$  will bring about a viscous flow. Cross-linking is when individual polymer chains are linked together by covalent bonds (joining of two atoms when they share a pair of electrons), to form one giant molecule.



**Fig. 3-2** Dependence of the tensile relaxation modulus  $E$  of an elastomeric material on temperature  $T$  for a fixed relaxation time  $t$ . Conversely, dependence of  $\ln E$  on  $\log$  of time  $t$  at a constant temperature is also represented by a curve of this shape.

One can conclude that one material could be a glass, or a leather, or a rubber, or a flowing liquid depending on an external parameter such as temperature. The word "leather" refers here to the state defined above, and does not imply a connection to natural leather.

Some polymer scientists and engineers use the words "rubbers" and "elastomer" interchangeably; others limit the former to materials in the rubbery state while an elastomer is a material which exhibits the behavior shown in Fig. 3-2. Thus according to the second definition, an elastomer can be found in the glassy state.

If an inverse procedure would be applied, that is for a constant tensile strain and now a constant temperature, to study the changes of  $\log F$  in function of time (more convenient  $\log t$ ), the resulting curve is of the same shape as that shown in Fig. 3-2. While the horizontal coordinate is different, it could be again glassy leathery, rubbery, and liquid states. While conducting an experiment on a time scale of a second it could be concluded that the material is glass. If the experiment would last many hours, the same material would exhibit properties of a rubber; the initial "protest" of the material against the imposition of a strain had been short-lived, the macro-molecular chains adapted themselves to the deformation (that is new length), and now only the rubbery type of response is detected. In other words, in a 100-year operation data will not be recorded more often than, say, once a week. Most of what was just called protest of material took place immediately after  $t=0$  when the constant strain had been imposed. The  $E(t)$  curve will miss important action, since after one week this action subsided.

If the varying parameters cannot be recorded at short time intervals, and at the same time missing the action in the beginning of the process is not preferred, there might be a way out: lowering the temperature considerably. At a lower  $T$  there will be less total volume, and, therefore, less free volume than before. Changes in polymer conformations and the resulting changes in properties will be slowed down, and one might be able to catch these changes on a convenient time scale. A procedure inverse to this one is also in use: if a process at the temperature of interest is very slow, the temperature could be increased and thus observe what is wanted without waiting for too long. In both procedures, the temperature was changed so as to change free volume. It is the latter which is the key to the situation.

### **3.3 DEGRADATION OF POLYMERS**

#### **3.3.1 Introduction**

The degradation of polymers upon exposure to adverse conditions depends on the macromolecular structure, the presence of additives, and the presence of contaminants commonly present 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.

Salman et al. (1997b) identified the main mechanisms that degrade geosynthetic polymers as either hydrolysis for polyester-based geosynthetics, or thermo-oxidation for polyolefin-based geosynthetics

#### **3.3.2 Hydrolytic Degradation**

Hydrolysis occurs when positively charged hydrogen ions ( $H^+$  in acidic or alkaline media attack the ester linkage thus breaking the polyester chain. This reduces the polymer chain length, 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 in ambient temperatures but is not negligible, considering the typical lifetime of a civil engineering structure. Accordingly, hydrolysis may affect fiberglass piling and reinforcement, which is typically made of glass vinyl ester.

### 3.3.3 Thermo-oxidative Degradation

Chain breakage and the associated reduction of strength of polyolefin-based materials depends on the presence of oxygen as well as temperature (Chien and Boss 1967). Thermo-oxidation 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 in ambient temperatures. Salmam et al. (1997a) estimated that approximately 50 years is required before a statistically significant change in the strength of polyolefin geosynthetics is observed at 20°C. An additional 35 years is 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 significantly longer time duration.



# Chapter Four

## ARRHENIUS MODELING TO PREDICT POLYMER DEGRADATION

### 4.1 DEFINITION

A methodology for the determination of the degradation of polymeric materials used in long-term applications such as plastic piles, geosynthetic landfill liners and covers, and reinforced retaining walls is the focus of this chapter.

This chapter is mainly based on a paper written by Robert M. Koerner et al under the name of "Arrhenius Modeling to Predict Geosynthetic Degradation". The main concern of the paper was geosynthetics, yet it is applicable to a wide range of polymeric materials.

The predictive technique most widely used for polymer degradation (and explained throughout this chapter) is based on temperature superposition principle and is called 'Arrhenius modeling'. It uses high-temperature incubation of polymeric material followed by some type of laboratory testing in order to extrapolate the experimental behavior to a site-specific lower temperature. The tacit assumption involved is that the material's behavior within the high temperature incubation is

constant within this range, and can be extrapolated to the lower temperature of practical interest.

## 4.2 INTRODUCTION AND BACKGROUND

The question of degradation of polymeric materials in a buried environment is being asked with alarming frequency as more and more of these materials are being used in permanent facilities. Applications such as plastic piles, solid waste liner systems, landfill covers systems, retaining walls, and slope reinforcement require service lifetimes of 100+ years. To the facility owner or regulator, as well as the civil engineer designer, the question is far from trivial. Even with material guarantees (some for as long as 20 years), the cost of replacing degraded or failed piles for example, is clearly unacceptable from an owner/operator point of view.

## 4.3 THE ARRHENIUS MODEL AND EQUATION

It is well established that chemical reactions of all types proceed more rapidly at higher temperatures than at lower temperatures (Koerner et al 1992). Sometimes the increase in the rate of reaction can be very dramatic for even a relatively modest rise in temperature. The reaction rate ( $R_r$ ) can be presented conceptually as follows (Morrison & Boyd, 1978):

$$R_r = (X)(Y)(Z) \quad (4-1)$$

where  $R_r$  = reaction rate;  $X$  = collision frequency,  $Y$  = energy factor; and  $Z$  = orientation factor (a probability).

Equation (1) can be stated more explicitly as follows:

number of reactions per unit volume per unit time =  
total number of collisions per unit volume per unit time  $\times$  fraction of collisions that  
have sufficient energy  $\times$  Fraction of collisions that have proper orientation.

The above equation applies for chemical reactions in the gas phase where kinetic energy is the major source of energy. The X term is determined by pressure, volume, temperature and concentration of the gas. The Y term is determined by (a) the energy distribution of the gas molecules (i.e. the velocity distribution, because in an ideal gas the energy is completely kinetic, i.e.  $\frac{1}{2}mv^2$  where  $m$  is the mass and  $v$  is the velocity) and (b) the activation energy,  $E_{act}$  for the reaction. The Z term is

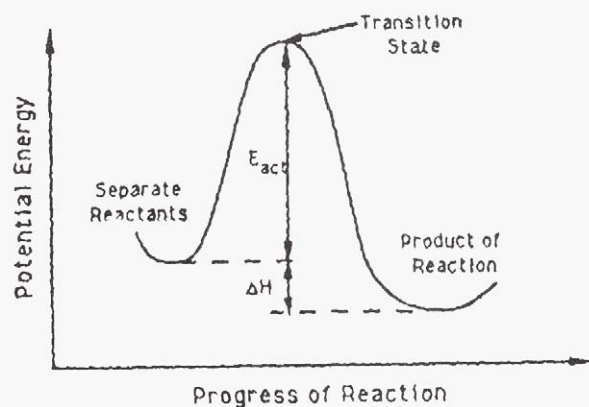


Fig. 4-1 Potential Energy Involved In The Progress Of An Assumed Reaction.

determined by how many of the colliding particles are properly oriented for the reaction. Of these terms, the Y term is by far the most important in determining reaction rates as a function of temperature. As will be seen, most reaction rates are highly dependent upon temperature.

Fig. 4-1 is a schematic diagram of the potential energy involved during the course of a reaction. The reactants must surmount an energy barrier,  $E_{\text{act}}$  (to assemble into an intermediate, or transition state) before going over into a changed, or reacted, state. The heat of reaction,  $\Delta H$ , is also shown. It is the net consumption of energy required for a chemical reaction. If positive, the reaction requires additional heat to progress and is endothermic. If negative (as illustrated), it dissipates heat as the reaction proceeds and is exothermic. Usually, little is known about the exact nature of the Transition State, but  $E_{\text{act}}$  can be determined experimentally without exact details as to the-transition state.

The distribution of velocities (i.e. energies) in an ideal gas was derived by Maxwell in 1852, and it is the usual bell-shaped (or Gaussian) curve common in statistics. This curve is shown in Fig. 4-2. The fraction of particles in Fig. 4-2 having energies greater than some value  $E_{\text{act}}$  is given by the relationship:

$$e^{-(E_{\text{act}}/RT)} \quad (4-2)$$

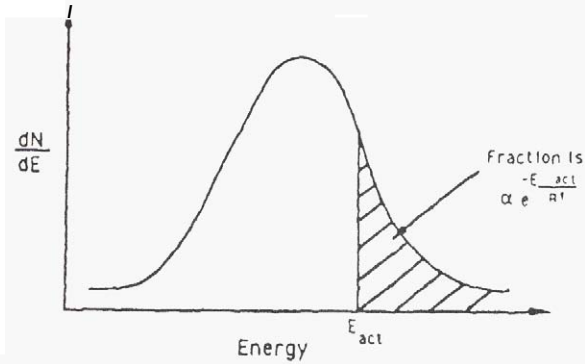
Where  $E_{\text{act}}$  = activation energy for the particular reaction (a 'typical' value might be 100 kJ/mol);  $R$  = the gas constant (8.31 J/mol K); and  $T$  = absolute temperature in kelvin, where  $K = ^\circ\text{C} + 273^\circ$ .

$E_{\text{act}}$  is fundamental to any particular reaction. It has been the focus of a significant amount of research and experimental investigation and will be seen to be critical in the work to follow.

Rewriting eqn (4-1) using relationship (4-2) for the Y term gives:

$$R_r = (X) \left( e^{-(E_{\text{act}}/RT)} \right) (Z) \quad (4-3)$$

*Arrhenius modeling to predict degradation*



**Fig. 4-2** Distribution of energy in an ideal gas where  $dN/dE$  = number of particles with energy between  $E$  and  $E + dE$ )

For simple gas phase reactions, the constants  $X$  and  $Z$  can be estimated reasonably well. The activation energy term  $E_{act}$  remains for experimental determination.

Assuming  $X$  and  $Z$  are independent of temperature and can be bracketed as a constant term  $A$ , rewrite eqn (4-3) as follows:

$$R_r = A e^{-(E_{act}/RT)} \quad (4-4)$$

Equation (4-4) is the most widely referenced form of the so-called Arrhenius equation. Note that the ratio of reaction rates at two different temperatures,  $T_1$  and  $T_2$ , can be written as follows, where the respective  $A$  terms from the two reaction rates cancel one another.

$$\frac{R_{r1}}{R_{r2}} = e^{-(E_{act}/R)[1/T_1 - 1/T_2]} \quad (4-5)$$

The above equation will be used throughout this chapter to predict the reaction rate at a site-specific temperature T2 from reaction rate data obtained at a high-temperature experiment T1. Generally the site-specific temperature will be significantly lower than the lowest test temperature and usually so low that to do laboratory experiments at this lower temperature would take excessively long time frames, e.g. many many years.

Taking the natural logarithm of both sides of eqn (4-4),

$$\ln R_t = \ln A - \frac{E_{act}}{RT}$$

If the log reaction rate is plotted against inverse temperature as shown in Fig. 4-3, the slope of the line will be  $-E_{act}/R$  and the intercept on the vertical axis will be the constant  $\ln A$ . For simplicity the ratio  $E_{act}/R$  will be used in subsequent calculations, recognizing that the activation energy  $E_{act}$  is the fundamental quantity which is used in many chemical reactions and has been extensively studied. Fig. 4-3 is called the 'Arrhenius Plot', and from it reaction rates at lower (site-specific) temperatures can be predicted by extrapolation from higher temperature experimental data. The equation has been used to predict long-term degradation of a wide range of materials, including many polymeric materials (Koerner et al 1992).

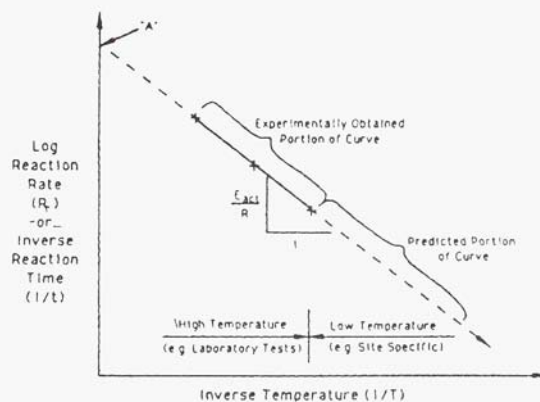


Fig. 4-3 Generalized Arrhenius plot used for low temperature prediction from high-temperature experimental data from laboratory tests.

It is essential in the method of low-temperature reaction rate prediction to obtain as much high-temperature data as possible (to ascertain if one single  $E_{act}$  value applies) and to make as small an extrapolation to the lower (site-specific) temperature as possible.

For reactions more involved than the gas reactions used in the theory just discussed, there can be very significant complications. This is probably the situation for processes involved in the degradation of polymers. The main problem is that instead of a single activation energy, there is often a distribution of activation energies. This reflects the multiplicity of 'reactions' that can lead to the final degraded product. Even the collision frequency term  $X$  in the solid state involves vibration (and rotational) kinetic energies which are much more difficult to describe than the kinetic energies of an ideal gas. The orientation factor  $Z$  is also very difficult to describe and is very much involved with the orientational entropy of the reaction (as it is also in the ideal gas case).

It is impossible without suitable experimentation) to know what, if any, mechanical, physical or chemical properties of a geosynthetic product will be governed by a single reaction rate theory over a reasonably wide temperature range. It remains for careful experimentation to sort out the behavior of the reaction rates and to assess its behavior and appropriateness for this type of analysis.

#### **4.4 POTENTIAL USE OF ARRHENIUS MODELING IN POLYMERS**

Table 4-1 gives the major polymer types in current use for the various types of plastic piling & geosynthetics. Of these, the largest database regarding prediction of degradation is for polyolefins (PP and PE) and polyester (PET). In particular, high-density polyethylene has been widely evaluated by the gas transmission pipeline and telephone cable shielding industries.

While the procedure to follow might have applicability to all of the polymeric materials listed in Table 4-1, a special caution is raised for those polymeric materials that are highly oriented as far as their molecular structure is concerned. For those geosynthetics which have high orientation effects imparted to the manufactured product (such as oriented geogrids, many geotextile fibers and certain pre-formed geocomposites), the high-temperature incubation will probably relax the molecular orientation resulting in the subsequent testing of a very different material. Such effects might result in a very non-linear activation energy or might be impossible to interpret. For these products, a separate set of control tests aimed at estimating the reorientation effects might be possible - but the dual procedure certainly promises to be tedious and expensive. Clearly, the initial focus of this type of modeling should be on plastic piles, geomembranes, geonets and geopipe, most of which have relatively little orientation and relatively low residual stress (Lord et al., 1991).



**Table 4-1** Most Widely Used Polymers In Different Plastic Piling & Geosynthetic Products (Estimated Percentage Of Total Market).

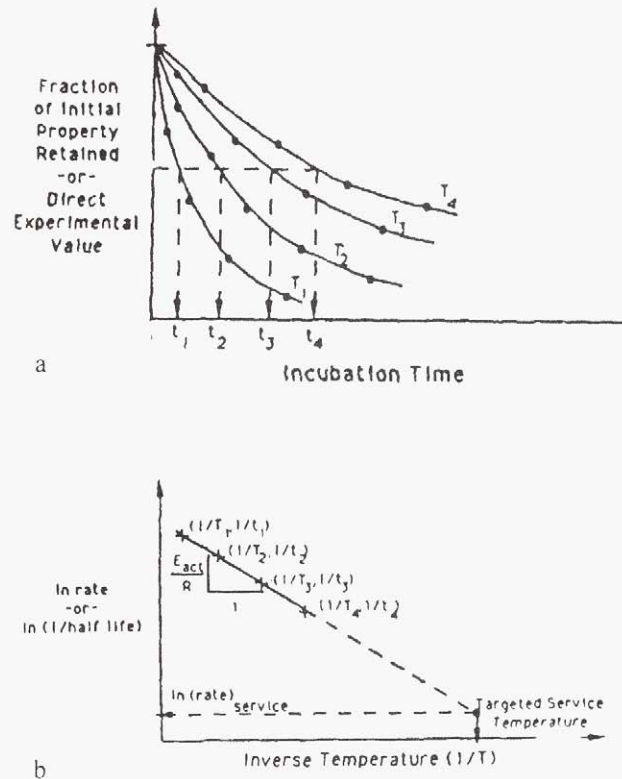
Polymer	Plastic Piles	Geo-textile	Geo-memb.	Geo-grids	Geo-nets	Geo-compos.	Geo-pipe
Polypropylene (PP)		65	-	15	-	15	-
Polyethylene (PE)	60	1	50	60	100	30	45
Polyester (PET)	30	30	-	25	-	15	-
(PVC)	-	-	25	-	-	10	45
CSPE	-	-	15	-	-	-	-
CPE	-	-	5	-	-	-	-
PS	-	4	5	-	-	15	10
Others	10					15	

As was mentioned earlier, a set of laboratory tests to generate experimental values is required for input into the Arrhenius model. These test values can come from a vast array of possible tests. One way of viewing the situation is to select a particular test method within either the mechanical, physical or chemical properties of the material.

The experimental procedure recommended by Koerner (1992) is as follows:

- (a) Incubate a set of representative polymeric test samples at a specific elevated temperature,  $T_1$ , in the site-specific liquid under consideration. ( $T_1$  will be the highest of the incubation temperatures to be described.)
- (b) Remove the first sample at an appropriate time and test it according to the selected type of testing.

(c) Take this result and compare it to the as-received, and unaged, value of the same property, to obtain a 'fraction of the initial property retained', or use the value directly as measured.



**Fig. 4-4** Conceptual use of strength loss in Arrhenius prediction to site-specific service conditions.  
 (a) Experimental property change data.  
 (b) Arrhenius graph of limiting service behavior.

(d) Plot the fraction retained (or the direct value) as a single point versus its corresponding incubation time. This is the first point on the  $T_1$  curve of Fig 4-4a.

(e) Continue this process with the entire set of samples incubated at temperature by removing them at gradually increasing times and testing them accordingly

- (f) Draw the entire curve labeled T1 through the generated points.
- (g) Repeat the entire process with a new set of samples, but now at a somewhat reduced temperature, T2. When all samples are tested, the curve on Fig. 4-4a labeled T2 should result. It is to be expected that if  $T2 < T1$ , the amount of retained property will be greater at an equivalent incubation time. Therefore the curves should become less steep and gradually less degraded as the incubation temperature decreases.
- (h) Develop experimental data for at least one additional temperature, T3. If the tests are not too lengthy, also develop data for a fourth temperature, T4.
- (i) With the three or four curves illustrated in Fig. 4-4a, select a designated value of property degradation that is desired. As mentioned previously, the 50% value (or half-life) has been used, but this is completely arbitrary. Other choices are a minimum acceptable value or a decided 'break' in the curves.
- (J) From the resulting values of half-life (or other selected value), obtain a unique set of degradation times corresponding to each incubation temperature.
- (k) Develop a second graph of natural logarithm of inverse half-life, or other designated value (as the y-axis) versus inverse temperature (as the x-axis) as shown in Fig.4-4b. This graph will have one point per incubation temperature. This is the Arrhenius graph or Arrhenius plot.
- (l) If the line connecting the data points is not linear (or at least nearly so), it suggests that either experimental inaccuracies occurred, that there is a distribution of activation energies, or that the elevated temperature has had an anomalous effect

on the polymer. In these latter cases, Arrhenius modeling is simply not appropriate. Highly oriented products might fit into this category.

(m) Calculate the slope of the line, which is  $-E_{act}/R$ , to estimate the degradation at a targeted service temperature which is lower than the temperatures at which the experiments were conducted. Note that calculations are not absolutely needed and that extrapolation on the Arrhenius graph to the desired temperature can be made directly.

#### **4.4.1 ARRHENIUS MODELING BASED ON STRENGTH BEHAVIOR**

Any one of a number of strength tests can be utilized in this group. Such as tensile, compression, tear, puncture, impact. Even within the tensile test category there is a wide range of test methods to select from, e.g. tests based on narrow strips, wide width or even on dumbbell-shaped specimens.

In this study unconfined compressive testing was used as an index test because it is believed that compressive strength of plastics is the most relevant property for piles.

# Chapter Five

## TESTING PROGRAM

### 5.1 OBJECTIVES

The comprehensive studies in the literature for virgin HDPE indicated that the rate of degradation by hydrolysis is negligible and can be neglected in some cases. However, in the context of the life time of civil engineering structures hydrolysis may be important considering where recycled plastics are often used. One of the objectives of this study is to verify that degradation due to hydrolysis has negligible effect on recycled plastics.

Environmental conditions which contribute to chemical degradation in polymeric materials include elevated temperature, UV radiation, exposure to oxygen, moisture, and acidic or basic environments. The relative importance of each of those factors is determined by the usage of the material. The degradation of specific polymers upon exposure to conditions that prevail in use depends on macro-molecular structure, on microstructure, on the presence of additives and Contaminants, and on chemical reactions resulting from the proximity of other materials in multi-component systems or end products.

The investigation of chemical degradation on the mechanical properties and durability of plastic piles products, should be designed with these considerations in mind. Furthermore awareness of the limitations imposed by laboratory simulations

of field conditions, and by the product composition and properties superimposed on those of the component polymers should also be considered.

In order to simulate the aggressive soil environment in the lab, aqueous solutions were used since it is simpler to control.

In order to assess the influence of pH of the environment on the rate of mechanical degradation the following environments have been selected:

- Neutral environment of water with pH=7
- Acidic environment of aqueous solution of  $\text{H}_2\text{SO}_4$  at pH=2
- Alkaline environment of aqueous solution of NaOH at pH=12

In order to achieve measurable changes of strength, within the limited laboratory time, the samples were aged at elevated temperatures (40, 55, & 75°C). Coupon specimens were subjected to the three prescribed environments at these three elevated temperature (9 reactors). Specimens were retrieved monthly from each reactor. Each retrieval contained at least five specimens for testing in unconfined compression, per ASTM D 695.

## **5.2 SCOPE OF STUDY**

The scope of this research is limited to the laboratory investigation of the accelerated degradation of Seaward International piling samples only (Seapile™). The experimental program is intended as an empirical investigation of the effects of specific environmental variables on the degradation process, if any, of the Seapile™ specimens. The product's service life, is also estimated with respect to being exposed to that specific aggressive media using the Arrhenius model.

The scope of this study is by necessity limited in that:

- Commercial plastic piling products are not well characterized, and generally contain residues and additives that can affect the chemical degradation mechanism. These additives and residues can make degradation more complex by causing secondary reaction to occur.
- To achieve measurable mechanical changes during the limited laboratory time Only severe conditions of treatment, as compared to the in-service conditions, are used to accelerate degradation.
- The plastic piling specimens are made of recycled plastics only.
- Unconfined compression testing of cylindrical 0.5 x 1.0 inches was used to assess the strength loss of the plastic piling samples.

The unconfined compression testing is considered to be an index test for establishing relative data for comparison reasons and not for assessing the strength of the material.

### **5.3 SAMPLE CHARACTERISTICS**

Seaward International produces its pile in 2 stages. First, a core made of recycled plastic is produced. Next, reinforcement is added & additional recycled HDPE is molded around the core. Seaward provided us with saw cut cross-sections of 10 inches diameter and approximately 1 inch thick. These samples were taken from the core of the pile's cross-section (Fig. 5-1a)

Cylindrical specimens 0.5" diameter x 1" long were punched out of these cores using a specially designed tool (Fig. 5-2). The resulting specimens have a length to

diameter ratio of 2:1 which meets the requirements of the ASTM D-695 standard for static compression test.

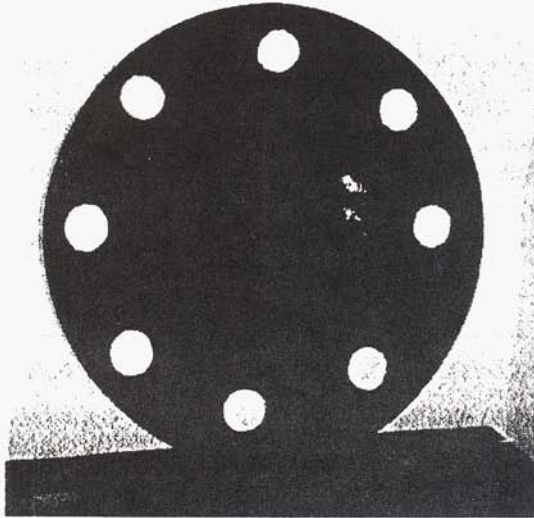


Fig. 5-1 a Pile Cross-section.

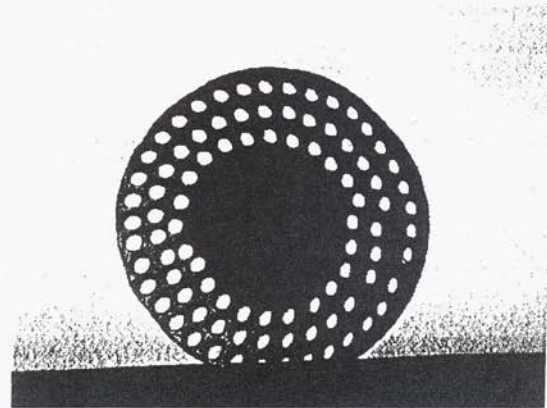


Fig. 5-1 b Punched Pile Core.

Since the core cross-sections are foamed at the center and almost solid at the edges, only three consecutive rows of each cross-section were used to avoid excessive variation in the mechanical properties of the specimens (Fig. 5-1b).



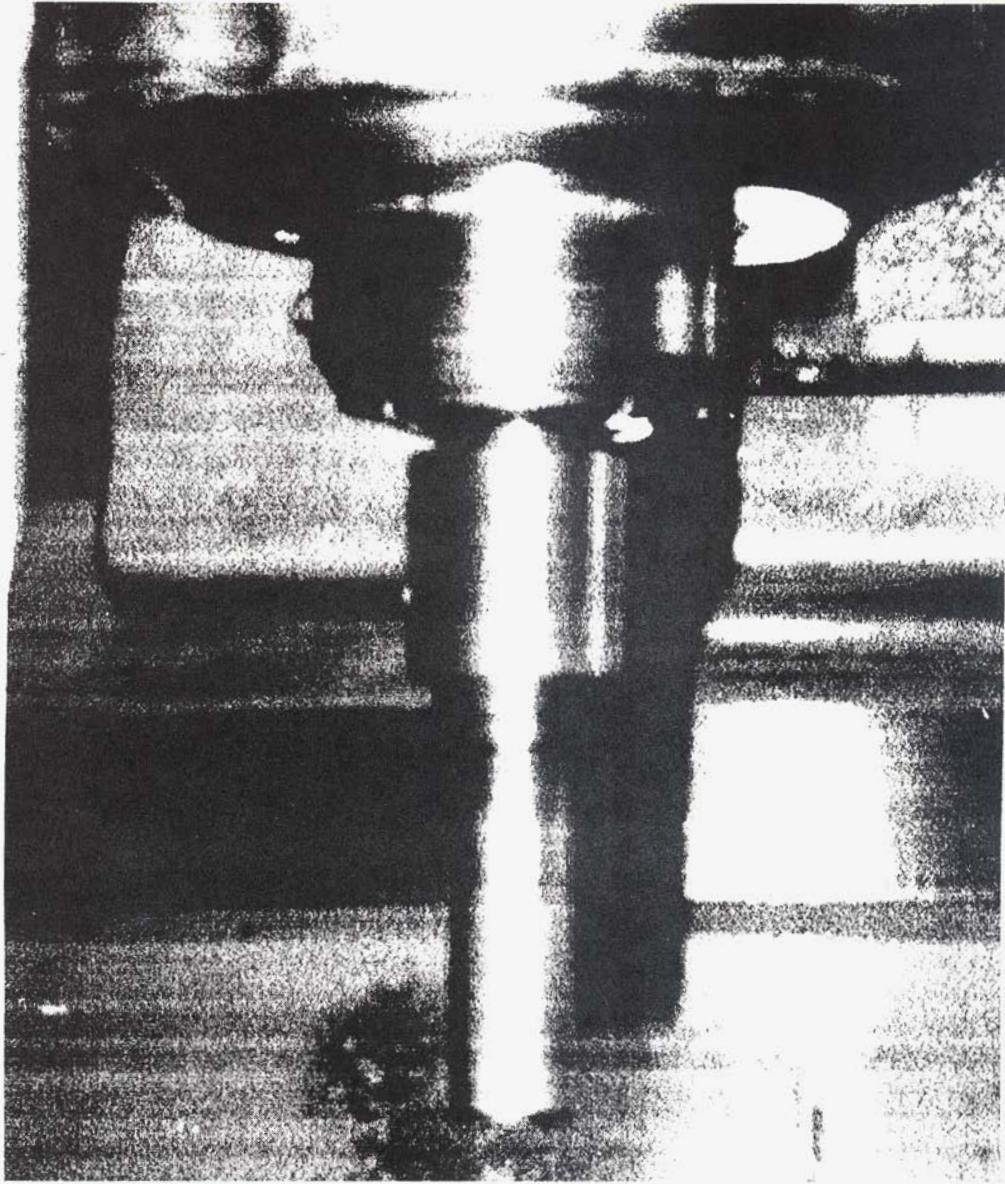


fig. 5-2 Punching Tool Used to Extract Testing Specimen

The weights, lengths, volumes, and densities of all specimens tested in this program are given in Appendix 1.

## 5.4 EXPERIMENTAL SETUP

### 5.4.1 Environmental Reactors

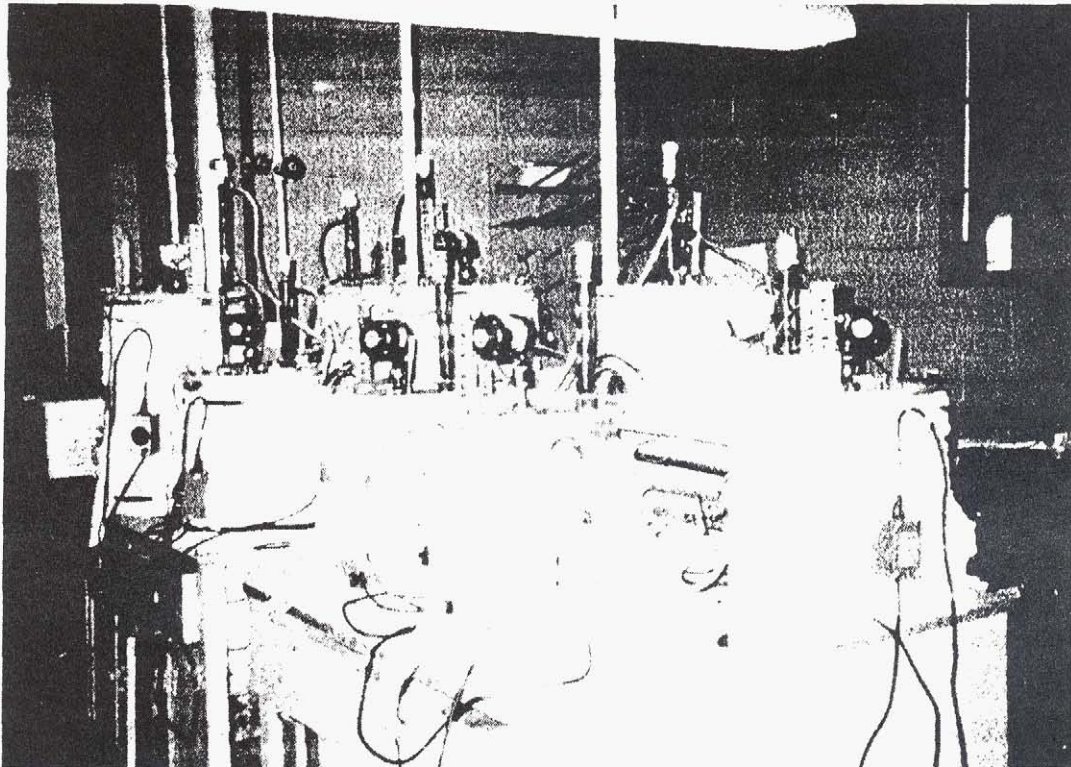


Fig. 5-3 Reactors Setup.

Nine stainless steel reactors were setup, as shown in Fig. 5-3, to study the effect of aggressive environmental media on the Seaward™ plastic piles specimens. These aggressive environments were represented by acidic, alkaline and neutral aqueous solutions.

Table (5-1) summarizes the reactors' different temperatures and the type of aqueous solution or environment media used. A set of three reactors represented each environmental media type. Each reactor had a different temperature of exposure 45, 55, or 75 °C. The selection of these specific exposure temperatures was based on a previous study that was carried out on similar polymeric materials (Salman et al 1997b) and also based on the Arrhenius modeling requirements, which requires at least 3 temperatures in order to predict the performance of the material at the lower in-service temperature.

**Table 5-1** Reactors Different Configurations.

Reactor #	Temp.	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



### 5.4.1 Reactor's Components

The reactor consists of a steel container heated by a heating system. An electric motor connected to a stirrer was fixed to the container in order to achieve a constant temperature and pH value in the reactor. Fig. 5-4 shows an external view of the reactor and Fig. 5-5 shows a schematic view of its components.

#### 5.4.1.1 STAINLESS STEEL REACTOR

Stainless steel containers were chosen for their proven ability to sustain high temperature of acidic and alkaline solutions. Five reactors were 1.5 feet diameter x 2 feet height, and 4 reactors were 1.25' diameter x 1.8' height. Each reactor had a Stainless steel cover, which was fitted with an electric motor, a condenser, a thermostat test tube and a thermometer. (Fig. 5-4). These covers were fastened on top of the container by means of a special steel clamp.

#### 5.4.1.2 HEATING SYSTEM

Each reactor was fitted with a heating system. The heating system consists of the electric heating strap, thermostat, fiberglass insulation, and thermometer for monitoring the temp of the solution. The

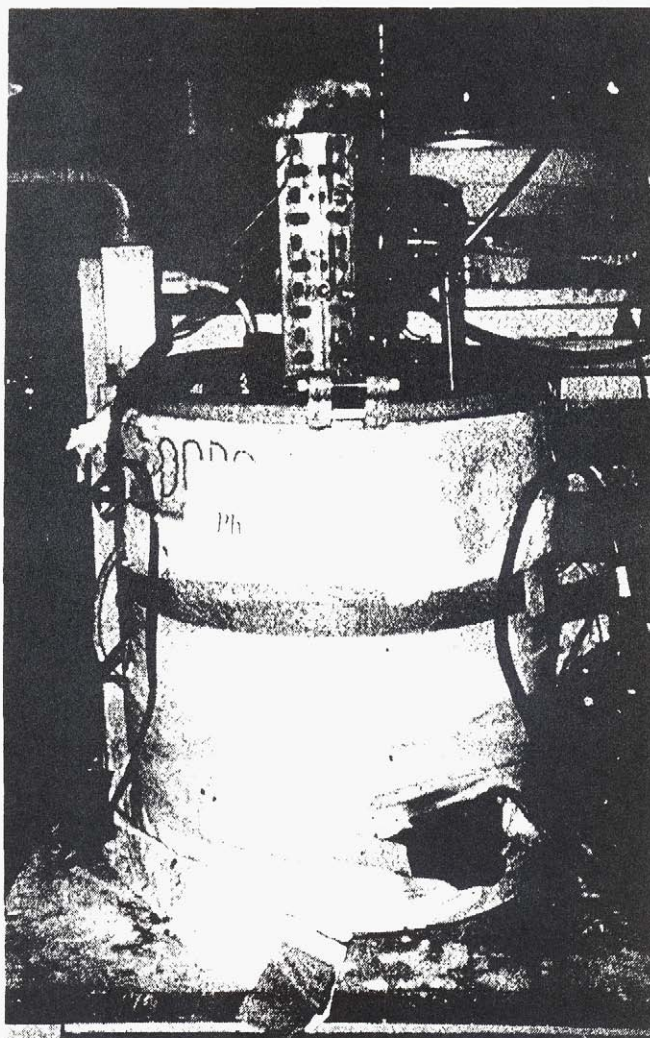


Fig. 5-4 External View The Environmental Reactor.

thermostat controls the heating strap to achieve the required temperature, i.e. when the temp of the solution drops under the thermostat pre-set temperature the thermostat closes the circuit, so that the electric tape starts heating up the stainless steel container, which heats up the solution, till the solution reaches the pre-set temperature then the thermostat opens the circuit.

The fiberglass insulation helps in keeping the reactor's temperature constant by preventing the dissipation of heat through the container's body.

#### **5.4.1.3 ELECTRIC MOTOR & STIRRER**

The agitator which is connected by a stainless steel shaft to The electric motor (Continuous running, rpm 290 and HP 1/70) are responsible for achieving a uniform temperature of the solution throughout the container. The motor's speed is reduced by a 6:1 gear ratio so that the actual speed of stirring is about 48 rpm.

#### **5.4.1.4 HYDRAULIC CONDENSER**

A condenser is used to keep the solution's level constant in the containers. The condenser consists of 2 glass tubes, internal and external. the internal tube is closed from top and opened from the bottom to receive the vapor. The external tube has an inlet, which is connected through a hose to a cold tap water source, and an outlet to a sink by another hose. While the water flows in the external tube it cools down the vapor in the internal tube, which in turn transfer back to the liquid state & falls into the reactor. By doing so the condenser keeps the solution's level constant in the container.

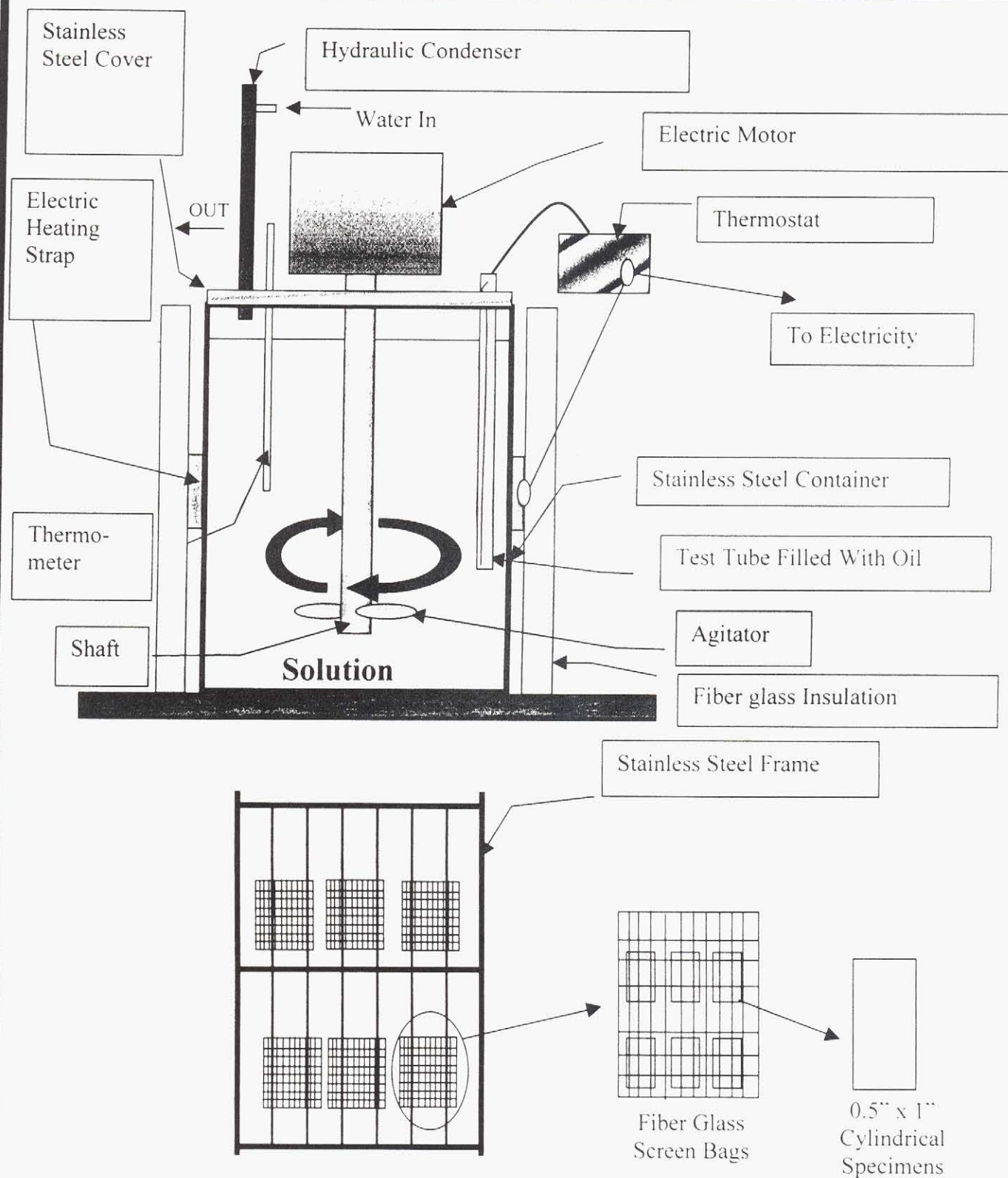


Fig. 5-5 Schematic View of Temperature Controlled Reactor.

#### **5.4.2 Loading frame**

The Loading frame used for performing the compression testing was simply the “Loadtrac” machine used for the tri-axial testing of soils. (Fig. 5-6). A load cell with a maximum capacity of 500 pounds was used to record the load. An LVDT with a maximum range of 0.5” was used to record the strain. The strain rate was set to 15%/min. and the tests were performed to a strain of 35%.

### **5.5 TESTING MATRIX.**

A total of 6 retrievals, in-addition to the as received specimens, were scheduled one retrieval per month for 6 months. Each retrieval had at least 5 samples to be tested in compression. During the incubation period the samples for each retrieval were kept custom made bags. The bags were custom made from screening material which is typically used in windows to screen insects. These bags were then tied to the stainless steel frames, which were inserted in the reactors to prevent the bags from floating to the surface of the liquid (Fig. 5-5).

The samples were weighted prior to. Length and weight after the exposure to the aggressive media was also recorded prior to compression testing. (See appendix I for a list of all the samples’ physical properties. No measurable change in weight was observed over the incubation period.



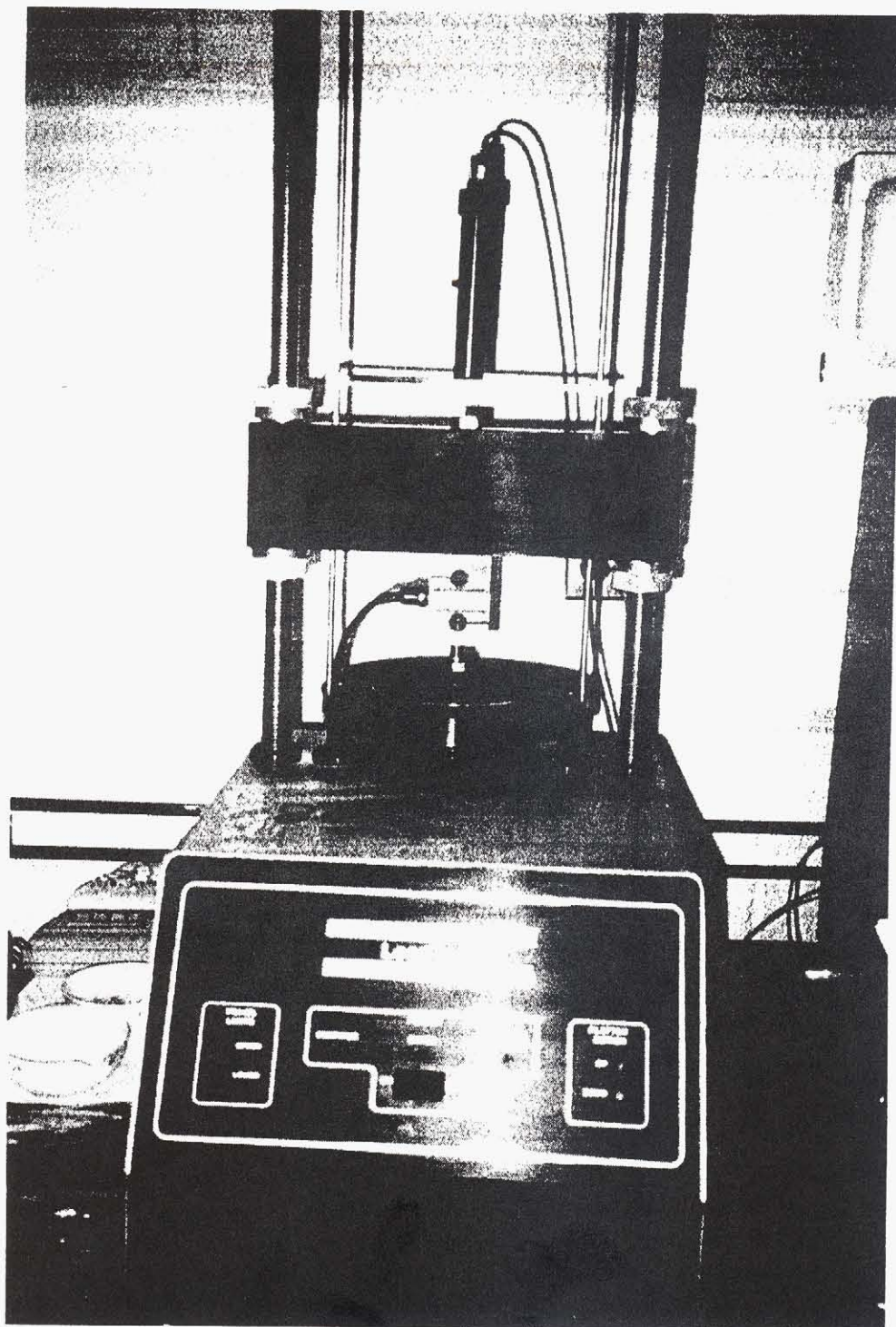


Fig. 5-6 The Loading Frame While Conducting An Unconfined Compression Test On a Seaward<sup>TM</sup> Specimen.



# Chapter Six

## TESTING RESULTS

A code number was assigned to each specimen in order to keep track of the data, and to make it easier to correlate and cross-reference the different variables. For instance specimen number 361 denotes reactor number 3, retrieval number 6, and specimen number 1 in that retrieval. Appendix I contains a complete list of the weights, volumes, and densities of all specimens.

### 6.1 PHYSICAL TEST RESULTS

The specimens were weighed before being installed in the reactors. The values were recorded to be compared with the values after the incubation period.

As discussed in chapter 3, there are two ways in which hydrolysis degrade polymers. The first is the molecular chain breakage, which does not affect specimen's weight. The second is surface erosion, which is manifested by weight loss.

After comparing the weight values, it was found that there was no significant difference between the weights before and after exposure to the aggressive media. These results confirmed that surface erosion did not take place, and that degradation process, if any, are be caused by chain breakage only.

## 6.2 STRENGTH TEST RESULTS

### 6.2.1 Introduction

Unconfined compressive tests were performed on 300 specimen according to ASTM D-695. Due to variability of plastic, ASTM D-695 requires that at least 5 specimens should be tested and the results averaged.

When the stress vs. strain data was plotted, for reactor 3 retrieval 6 (as an example) curves shown in Fig. 6-1a, did not fall in the same range. A large scatter was observed for specimens in the same retrieval. After a closer investigation of the data, it was discovered that this variation may be attributed to the difference in densities among the specimens. This difference in densities is caused in part from the fact that the specimens were punched from Seapile™ core samples which are foamed at the center and almost solid near the edges. In addition the manufacturing process could have resulted in variation in strength of the parent material across the cross section.

The bar chart in Fig 6-2 shows the density distribution of all the specimen used in this study. The specimens can be divided into 3 groups, light (0.48-0.60 gm/cm<sup>3</sup>), medium (0.60-0.70 gm/cm<sup>3</sup>), and heavy (0.70-0.88 gm/cm<sup>3</sup>). These three groups where formed presumably because the specimens were taken from three consecutive rows from the circular core mentioned above (Fig. 5-2).

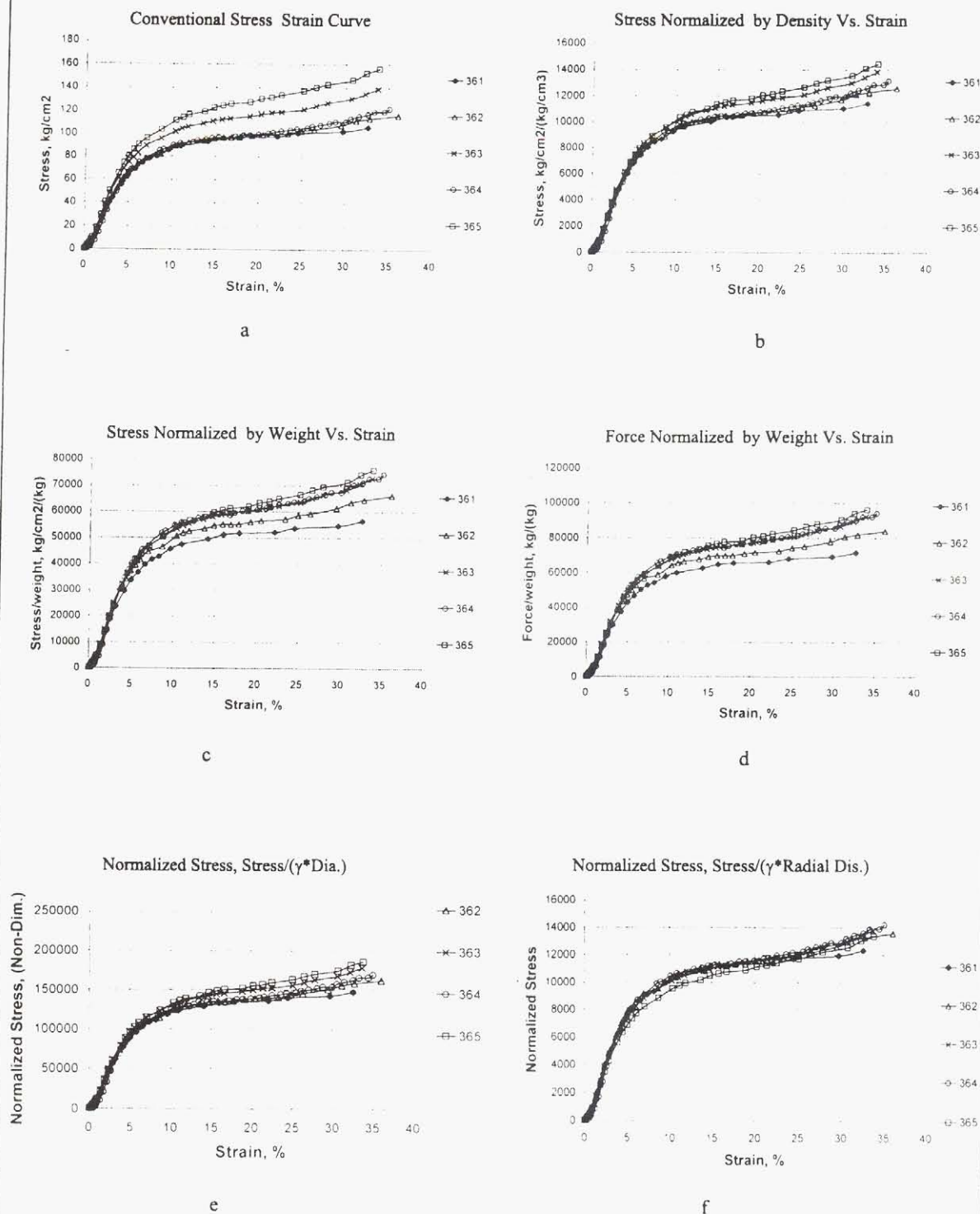


Fig.6-1 Different Methods Investigated For Data Reduction

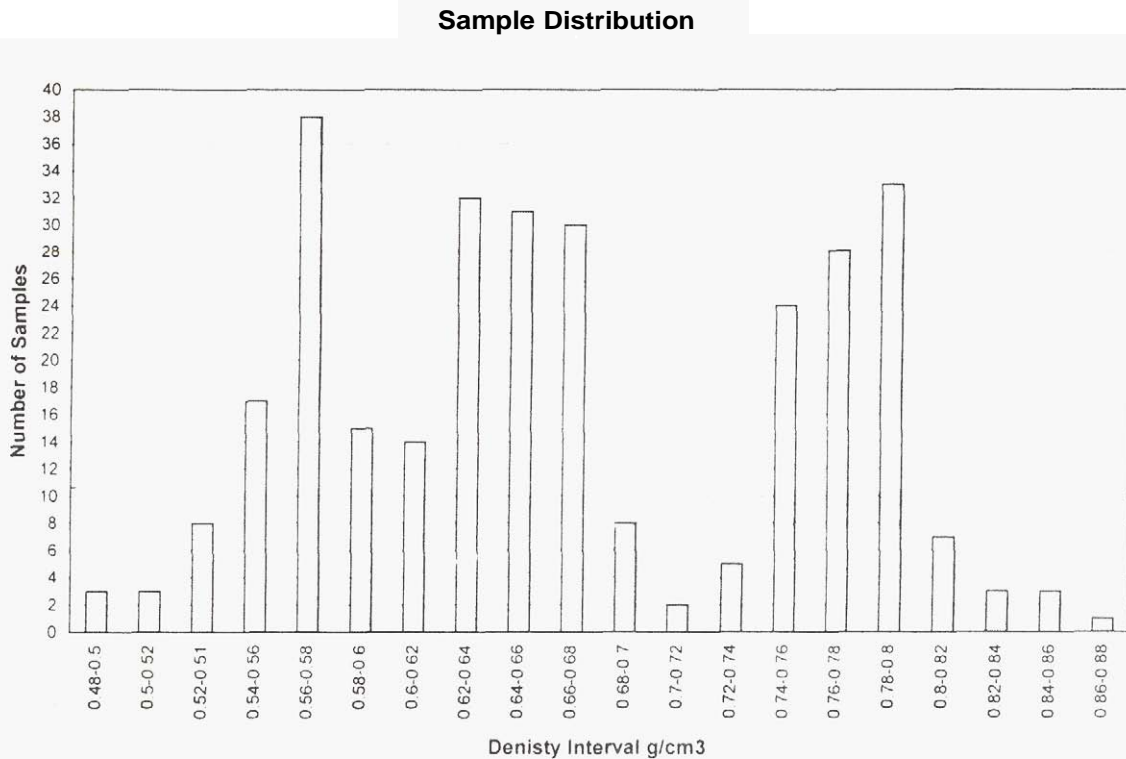
### 6.2.2 Different Methods investigated for data reduction

In order to reduce the data scatter, five different methods were investigated to normalize the stress strain data in full

1. Normalizing the stress (kg/cm<sup>2</sup>) by the weight of the specimen. (Fig. 6-1b)
2. Normalizing the stress (kg/cm<sup>2</sup>) by the density (kg/cm<sup>3</sup>) of the specimen (Fig. 6-1c)
3. Normalizing the force (kg), by the the weight (kg) of the specimen and plotting the result against the strain(%). (Fig. 6-1d)
4. Normalizing the stress by the non dimensional term  $\sigma/\gamma D$  (Fig. 6-1 e). where:-  
 $\sigma$  = stress psi  
 $\gamma$  = density pci  
 $D$  = diameter of specimen (0.5 inches)
5. Normalizing the stress by the non dimensional term  $\sigma/\gamma R$  (Fig. 6-1f). where:-  
 $\sigma$  = stress psi  
 $\delta$  = density pci  
 $R$  = radial distance from center of Seapile<sup>TM</sup> to center of specimen

Method number five from the previous list was adapted for all the test results, since it reduced the data scatter in the curves that fall in the same range of density described before and shown in the bar chart in Fig. 6-2. This method is based on a dimensional analysis discussed next.

All the stress strain curves obtained after degrading the specimens are shown using method 4 in Figs 6-3 to 6-11 and using method 6 in Figs. 6-12 to 6-20.



**Fig. 6-2** Sample Distribution With Respect To Density gm/cm³

### 6.2.3 Dimensional Analysis

The following are the steps followed to reach what the author and his Advisor called the "Characteristic Stress" which is a non dimensional term involving the density of each individual specimen  $\gamma$ , radial distance from center of core to center of specimen R, and applied stress  $\sigma$ .

In order to obtain a non-dimension  $\pi$  term, the relevant parameters are arranged as follows:

$$(\gamma)^d (R)^h (\sigma)^i = 1 \text{ --- (6 - 1)}$$

Expressing the terms by their fundamental dimensional units

$$\left( \frac{F}{L^3} \right)^a (L)^b \left( \frac{F}{L^2} \right)^c = 1$$

By equating the Force powers

$$a+c = 0$$

$$a = -c \quad (6 - 2)$$

By equating the length powers

$$-3a + b - 2c = 0$$

$$b = 3a + 2c \quad (6 - 3)$$

If

$$a = -1$$

Substitute in equ. (6-2)

$$C=1$$

Substitute in equ. (6-3)

$$b=-1$$

Substitute in equ. (6-1) by the values of a, b, & c

$$(\gamma)^{-1} (R)^{-1} (\sigma)^1 = 1$$

The non-dimensional  $\pi$  term is:

$$\pi = \frac{\sigma}{\gamma \cdot R}$$

## 6.2.4 Compression Testing Results

### 6.2.4.1 AS RECEIVED TESTING RESULTS

Six Seapile™ specimens were tested in their as received condition. The results are shown in Fig. 6-3.

### 6.2.4.2 AGED TESTING RESULTS

The following stress strain figures show the testing results after using the normalization methods number 4 and 5 discussed in a previous section of this chapter. These results are shown in Figs. 6-4 to 6-12 and Fig. 6-13 to 6-21 for methods 4 and 5 respectively).

It should be noted that the testing results obtained from method 5 were used in the analysis in the following chapter, since a big reduction of a data scatter was noticed after using this method of normalization.

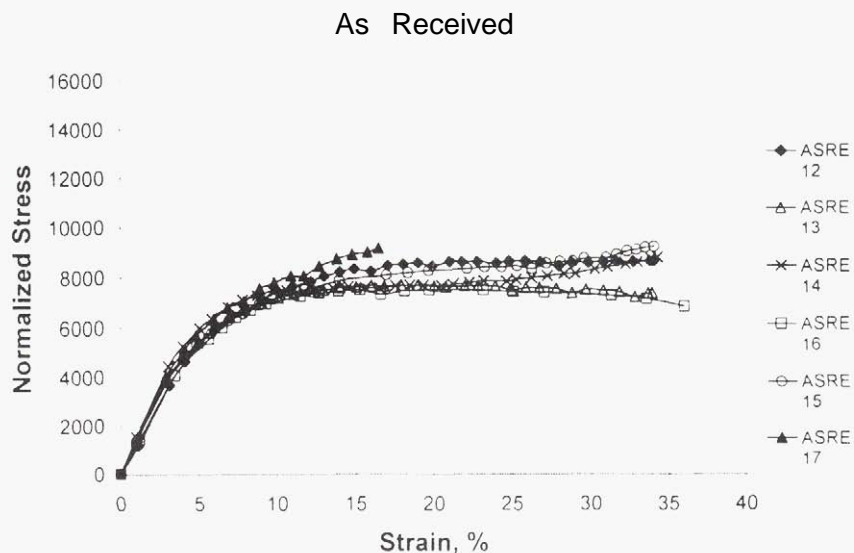
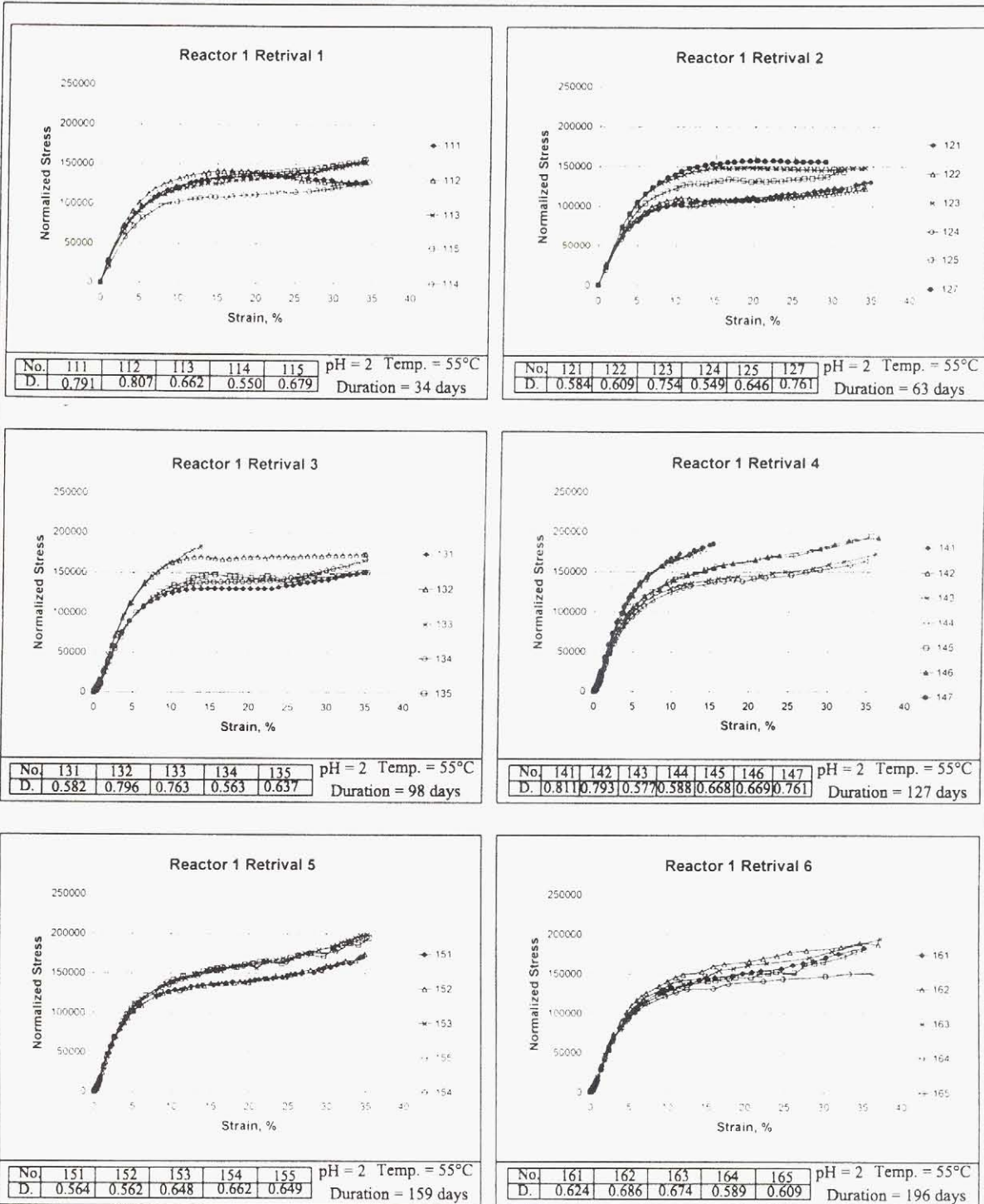


Fig. 6-3 As Received Compression Testing Results Using normalization method number 6.

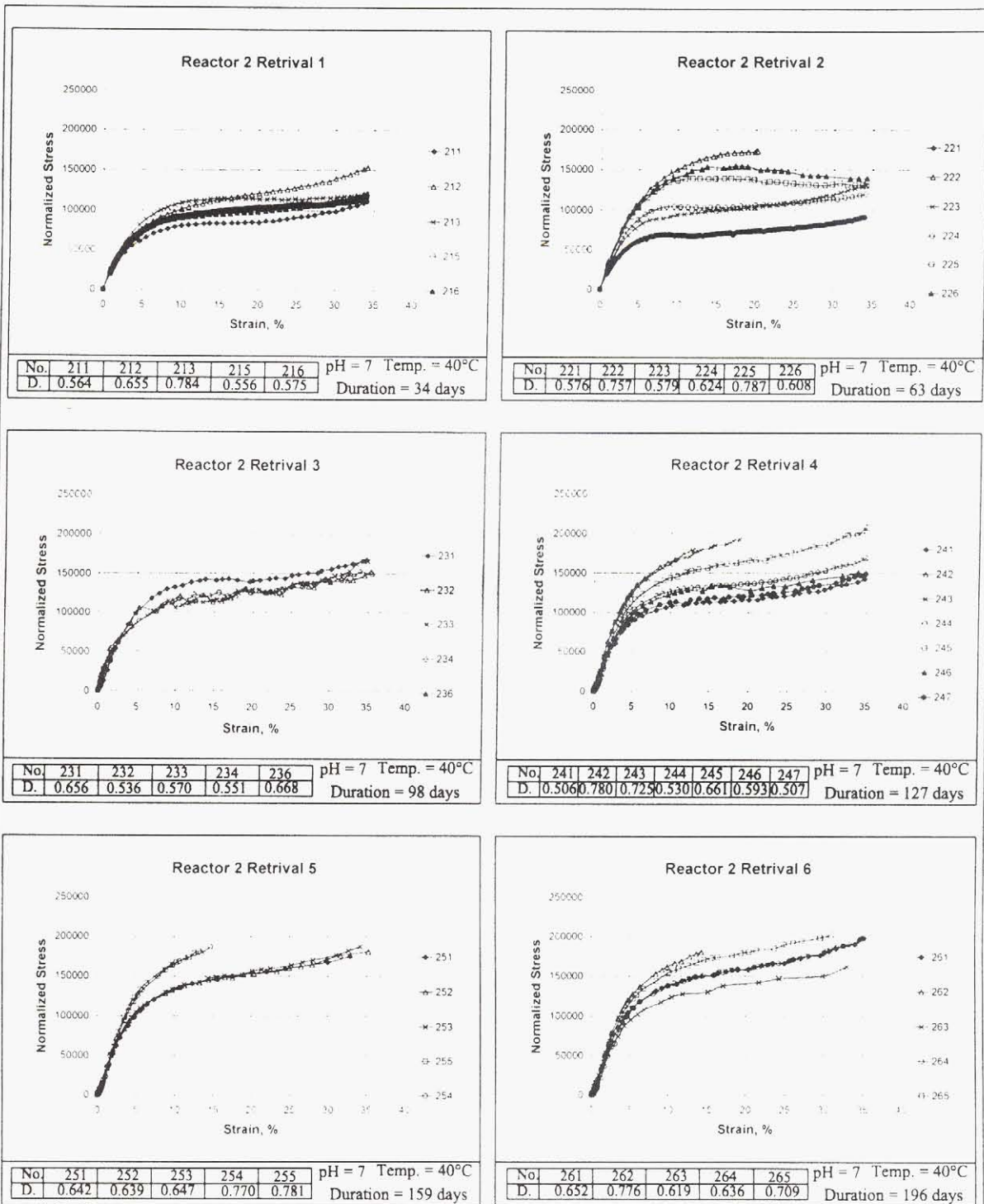


**Fig.6-4** Normalized Stress Strain Curves for Reactor No. 1

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D.= Density of each specimen expressed in gm/cm<sup>3</sup>

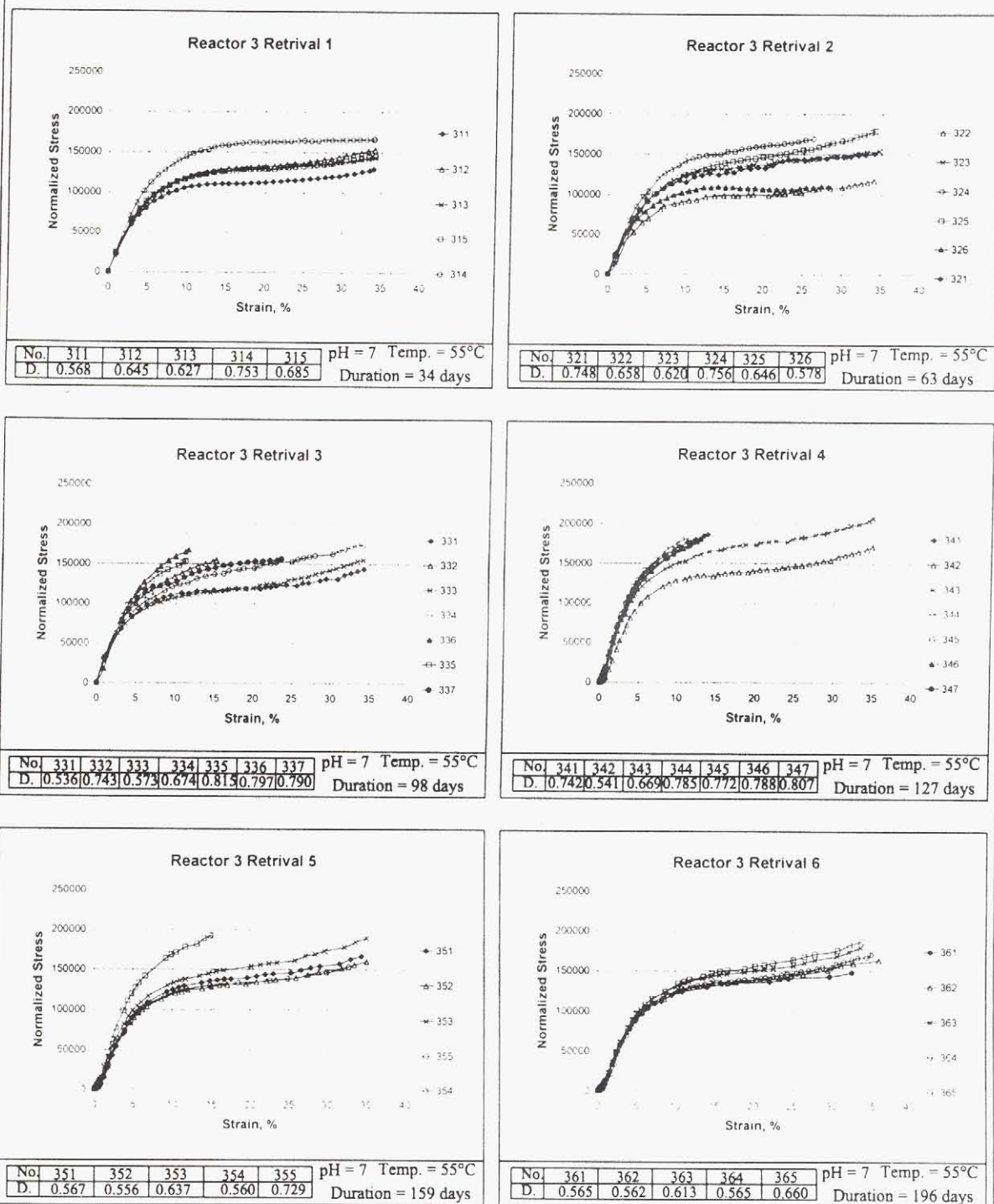




**Fig.6-5** Normalized Stress Strain Curves for Reactor No. 2

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

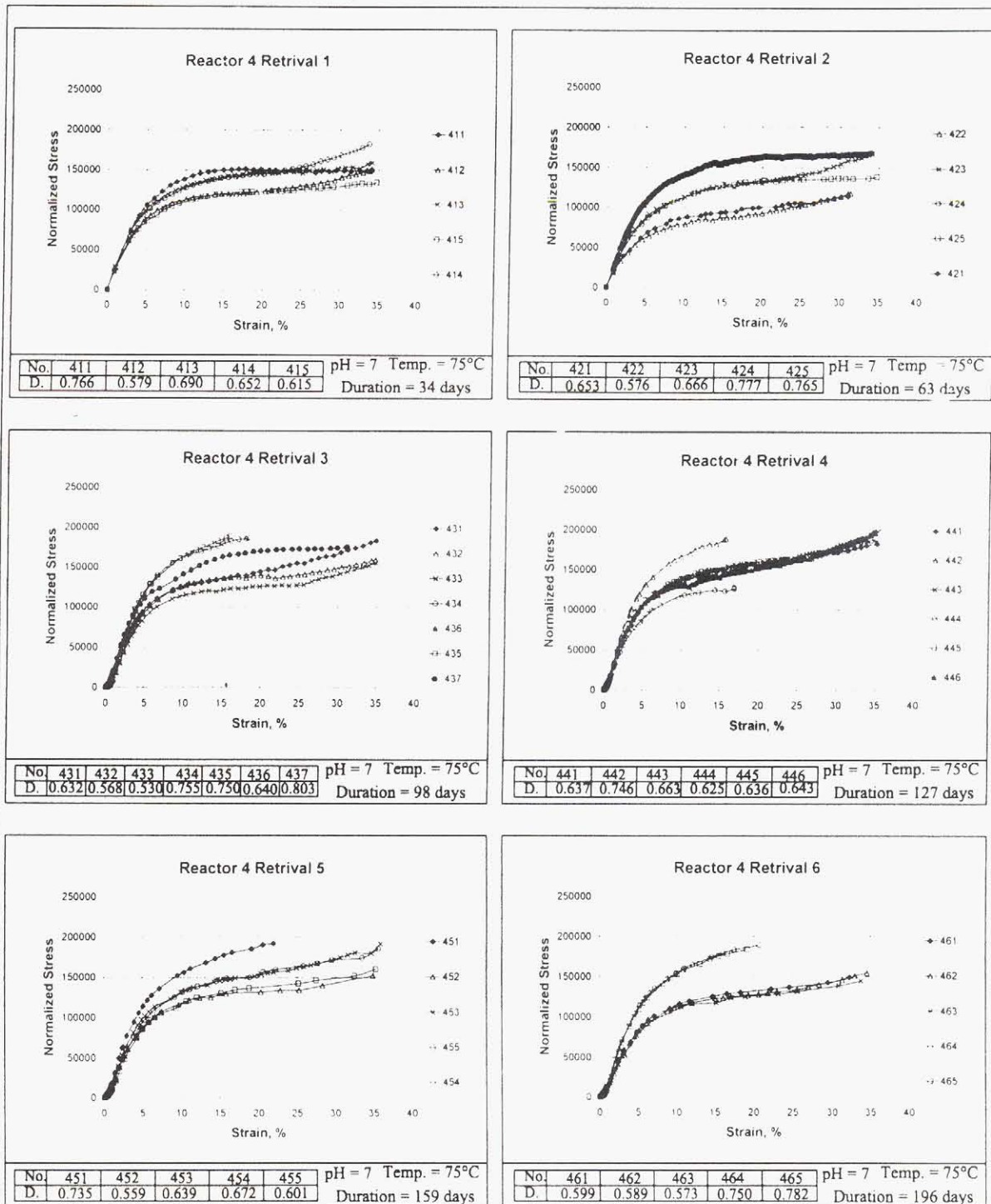
D. = Density of each specimen expressed in gm/cm<sup>3</sup>



**Fig.6-6** Normalized Stress Strain Curves for Reactor No. 3

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D.= Density of each specimen expressed in gm/cm<sup>3</sup>

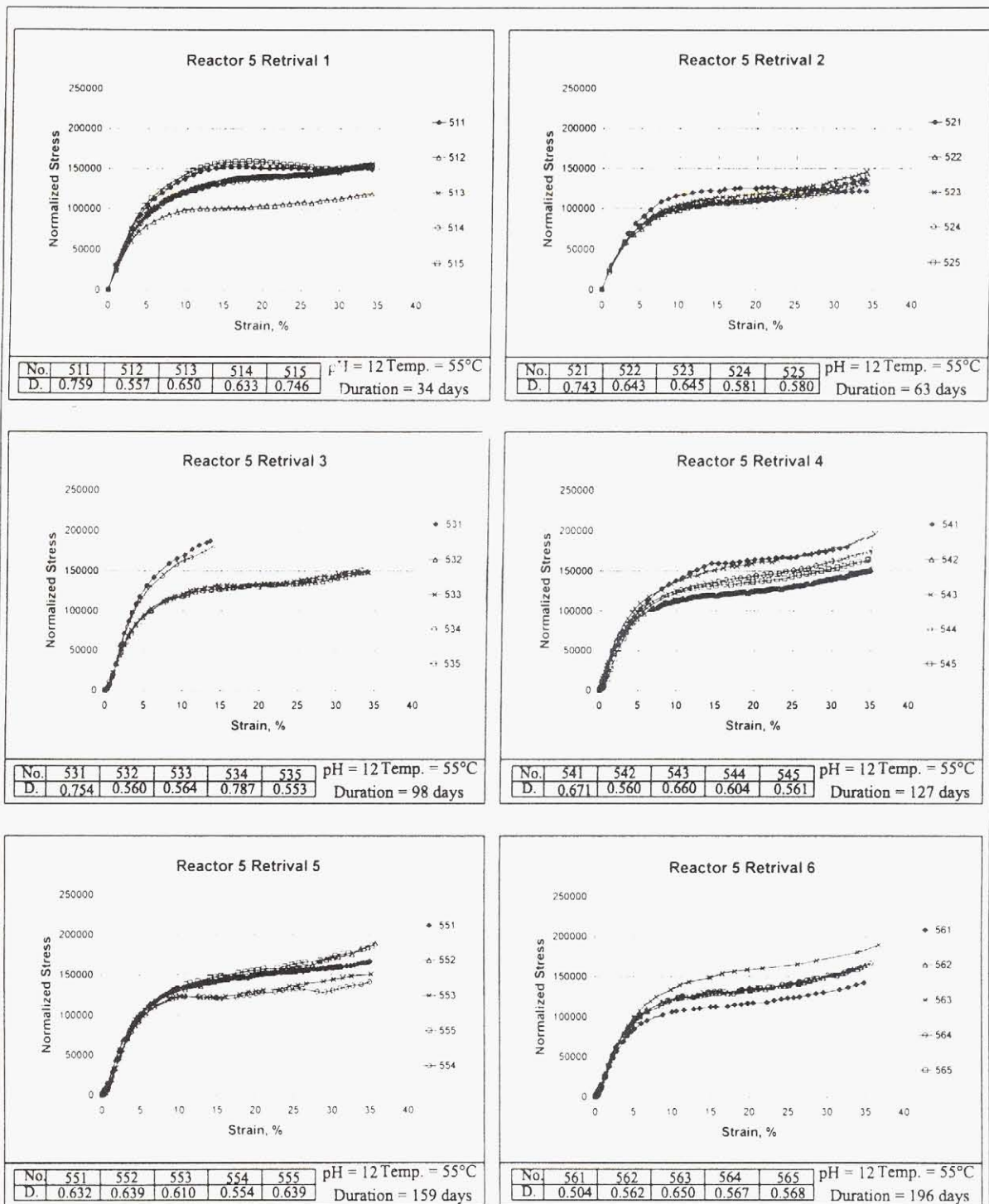


**Fig.6-7** Normalized Stress Strain Curves for Reactor No. 4

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D.= Density of each specimen expressed in gm/cm<sup>3</sup>

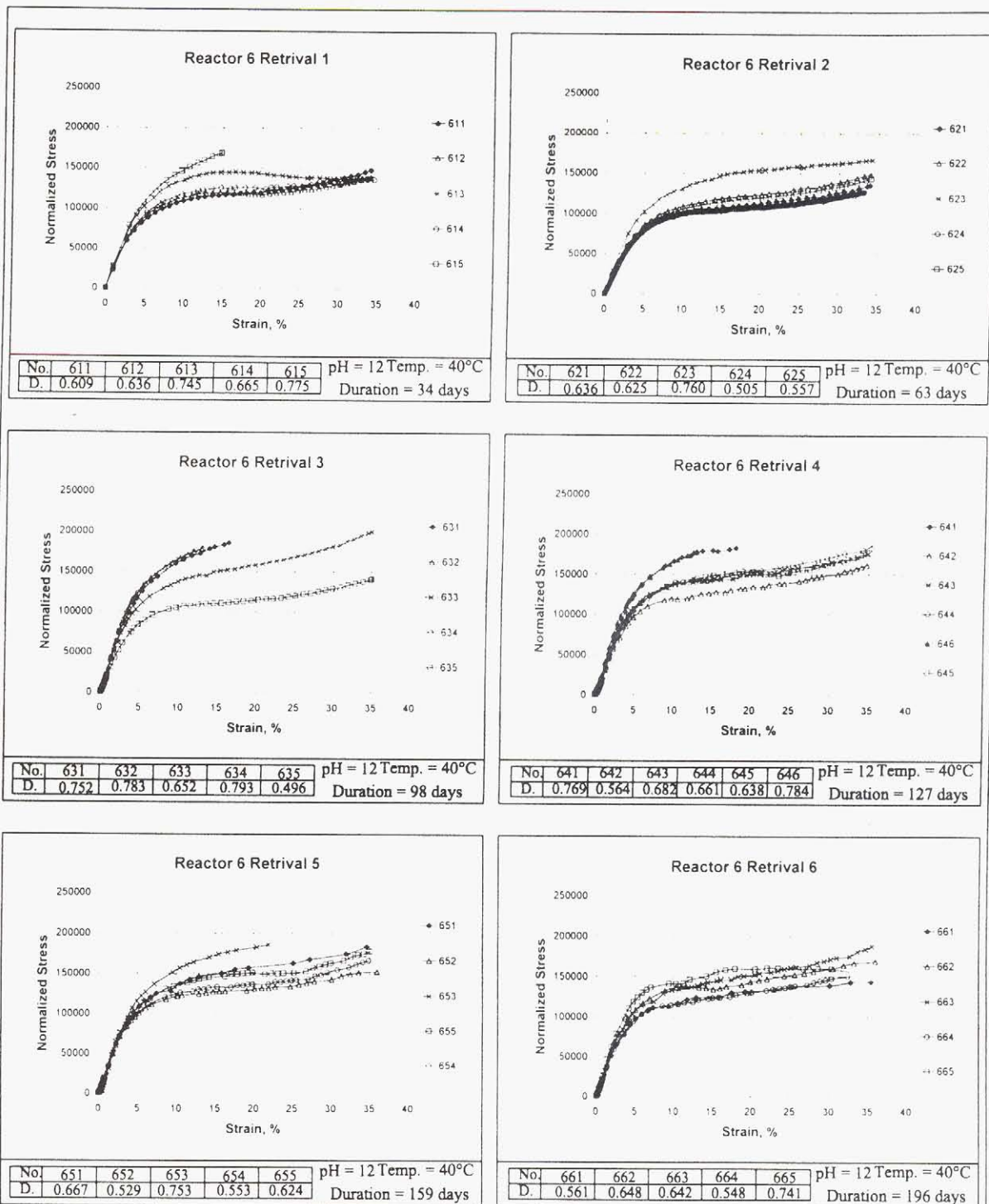




**Fig.6-8** Normalized Stress Strain Curves for Reactor No. 5

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

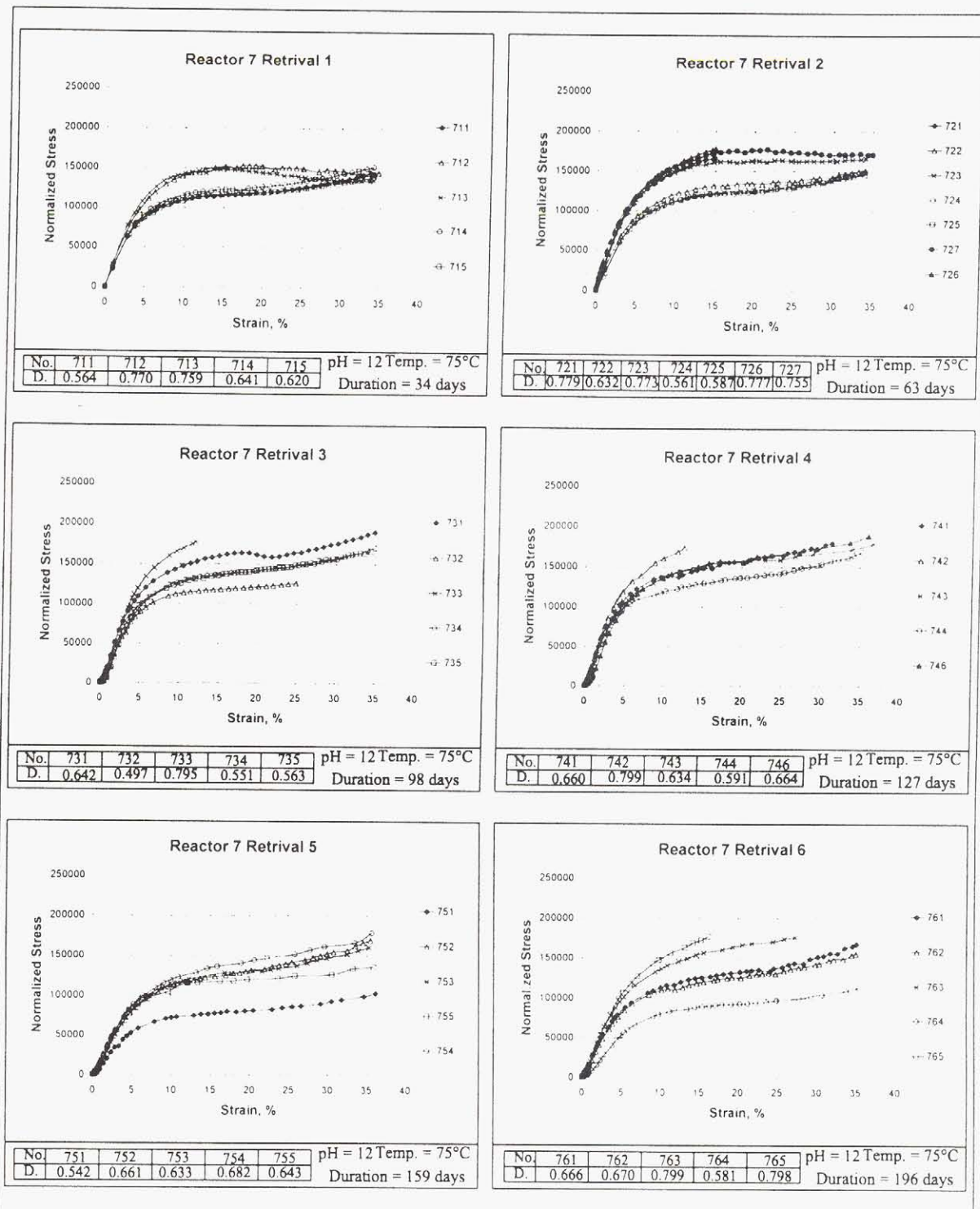
D.= Density of each specimen expressed in gm/cm3



**Fig.6-9** Normalized Stress Strain Curves for Reactor No. 6

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>

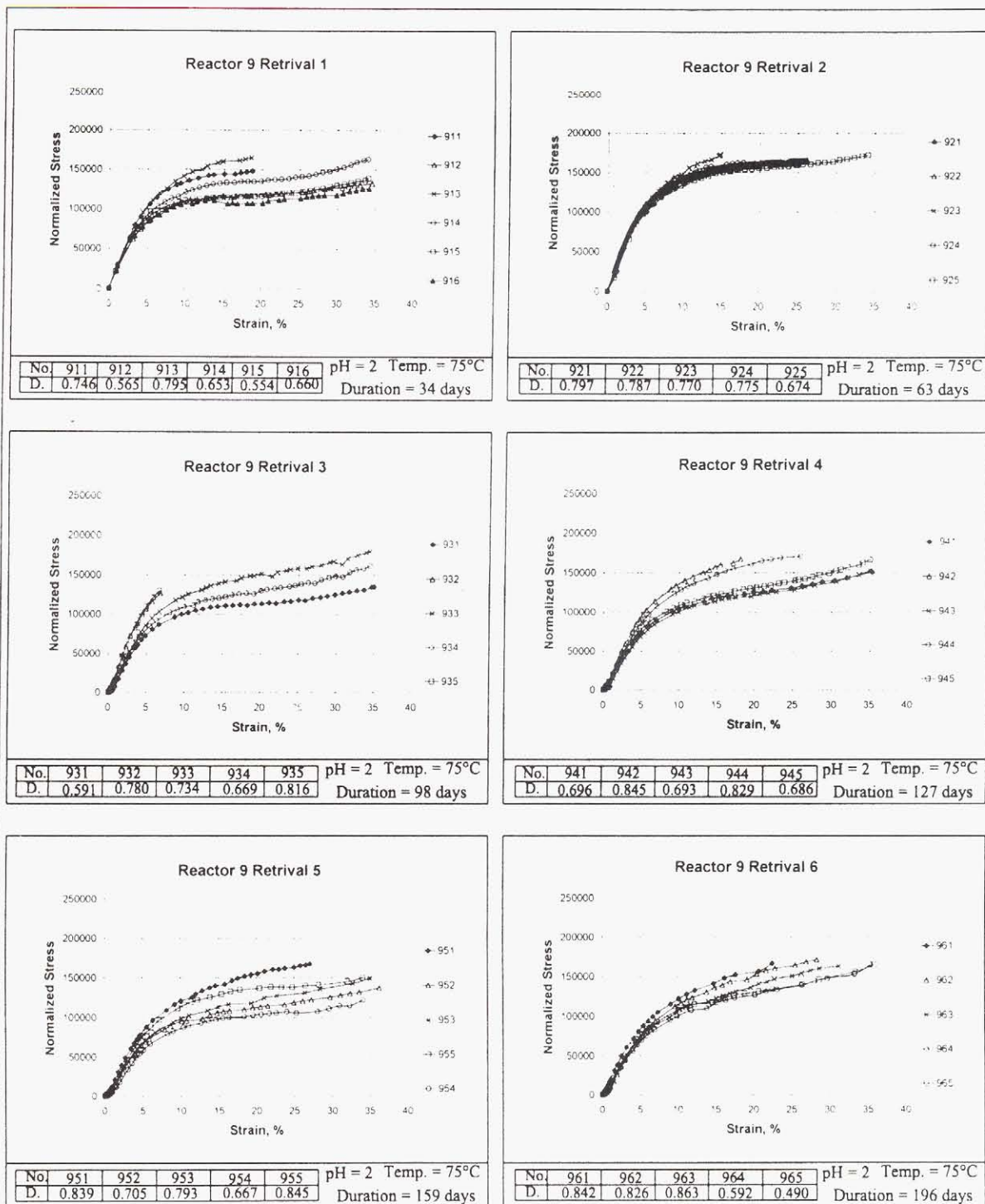


**Fig.6-10** Normalized Stress Strain Curves for Reactor No. 7

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D.= Density of each specimen expressed in gm/cm<sup>3</sup>

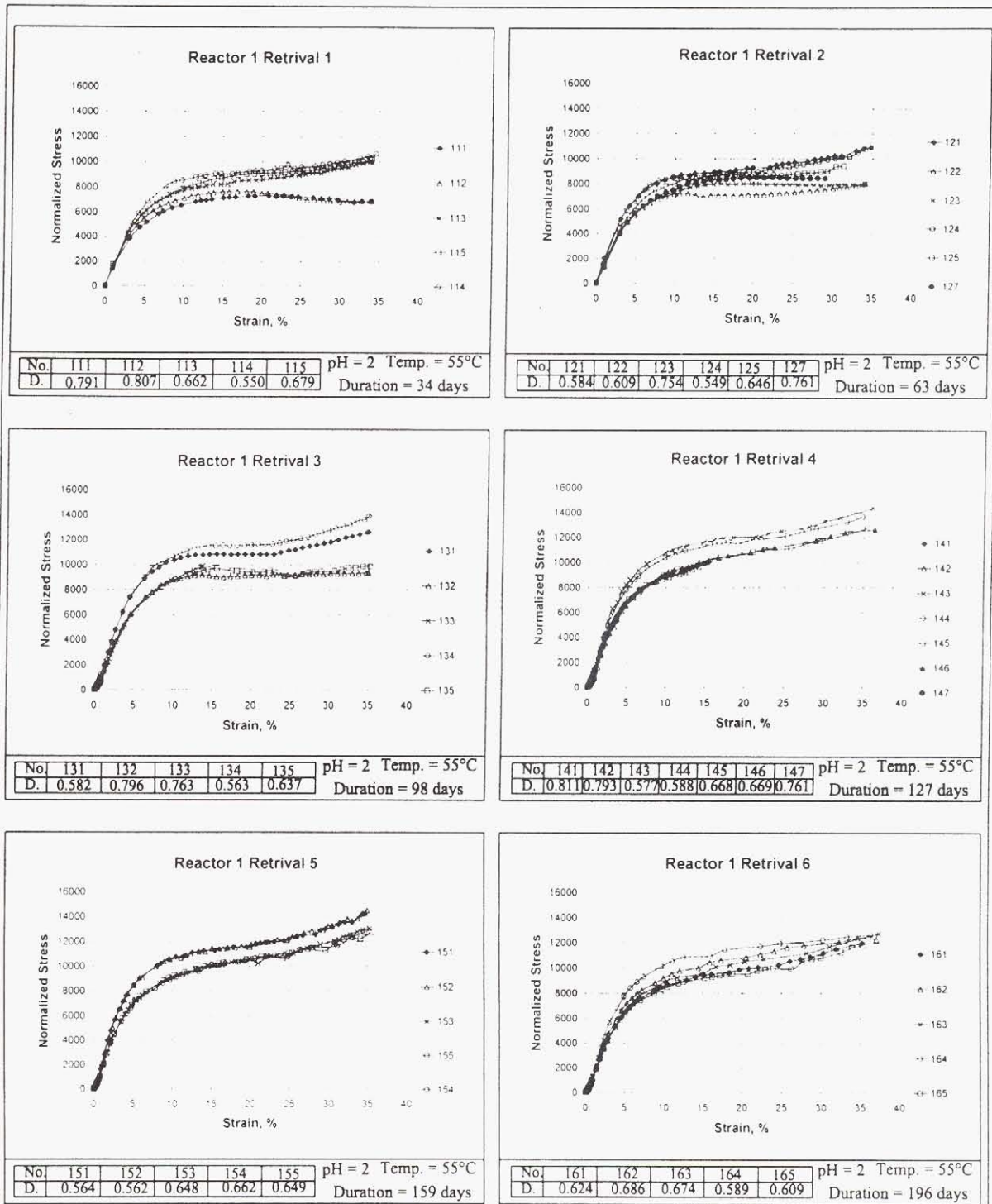




**Fig.6-12** Normalized Stress Strain Curves for Reactor No. 9

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>

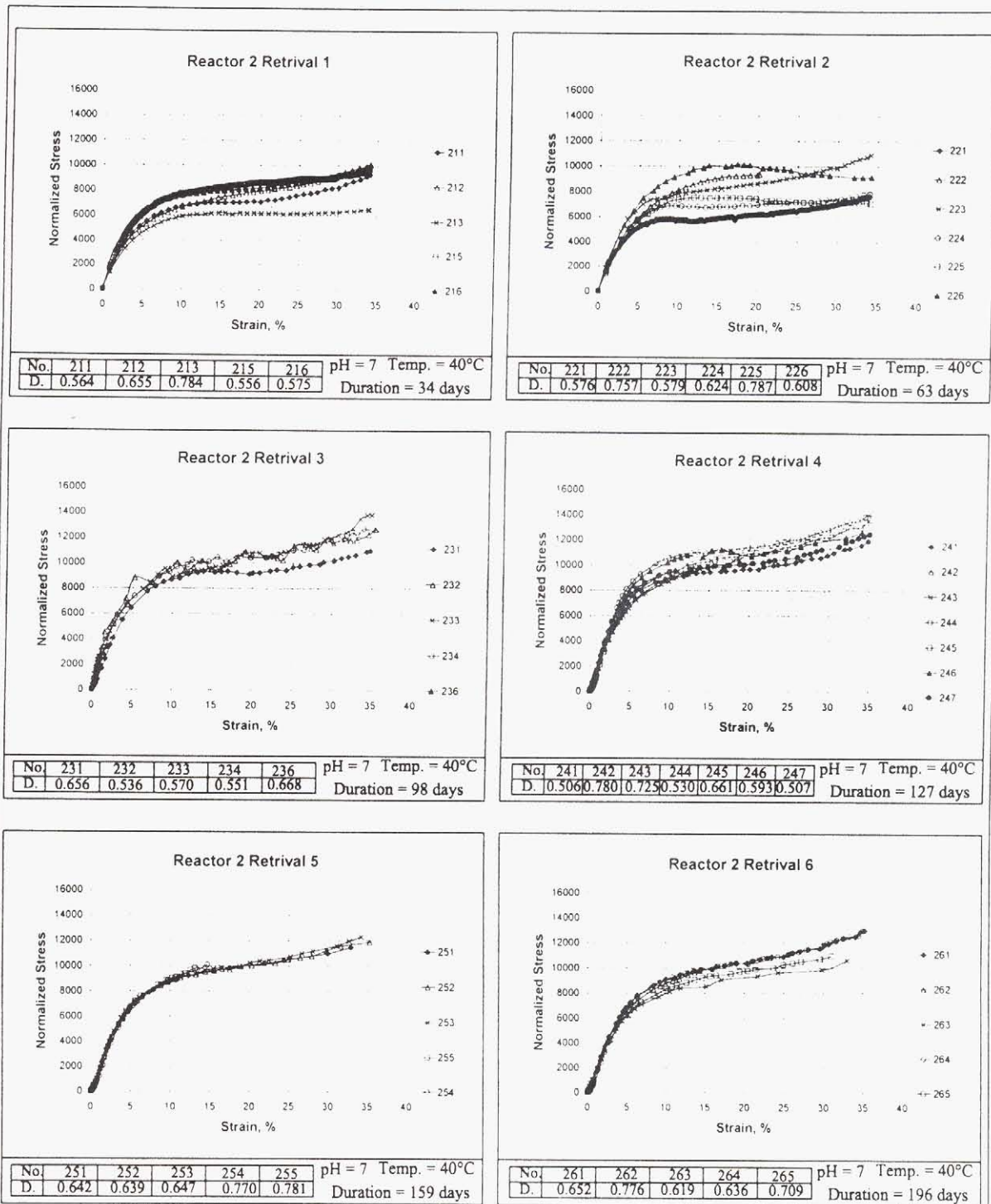


**Fig.6-13 Stress Strain Curve for Reactor # 1 Normalized by Denisty & Location**

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>

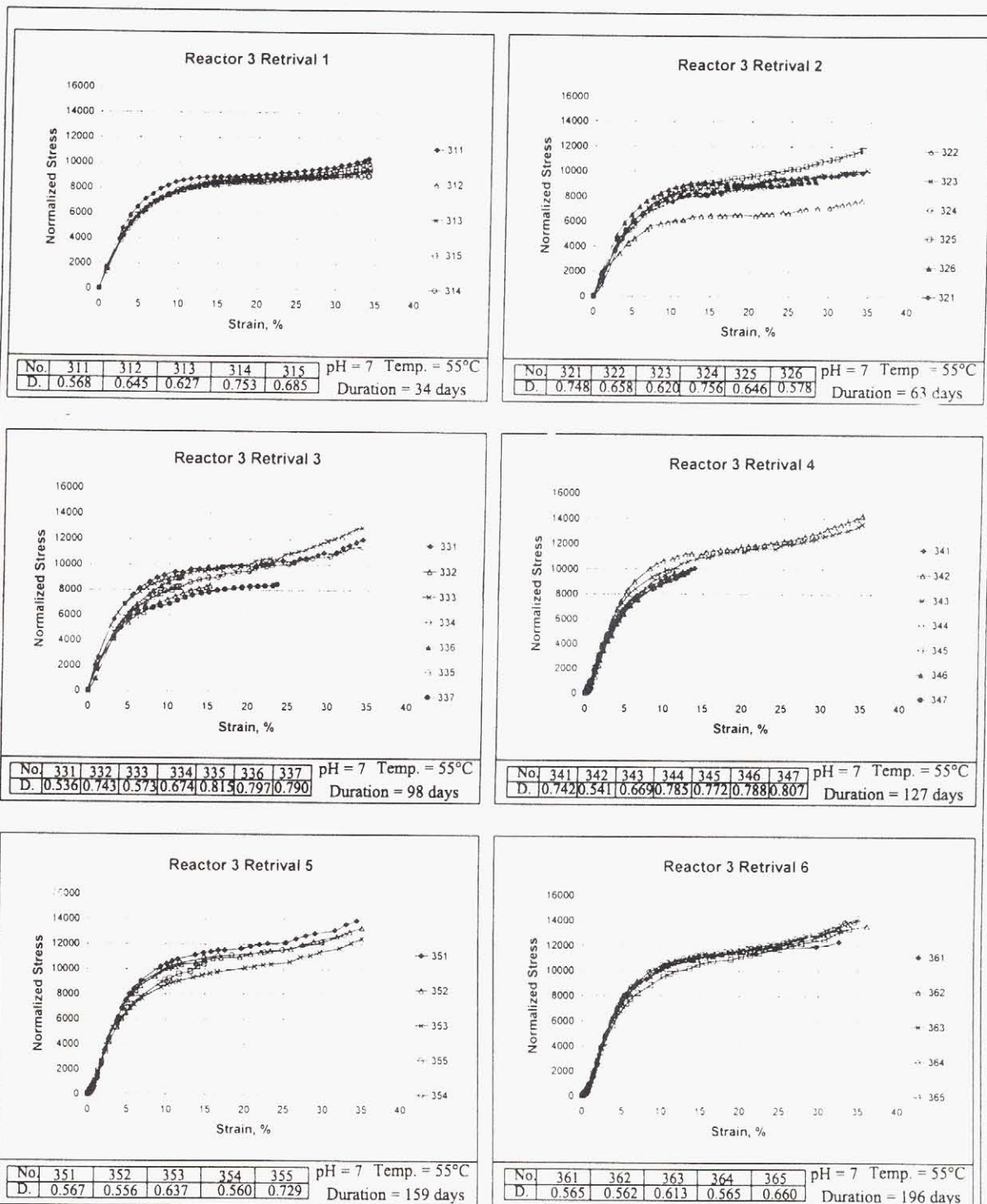




**Fig.6-14** Stress Strain Curve for Reactor # 2 Normalized by Denisty & Location

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

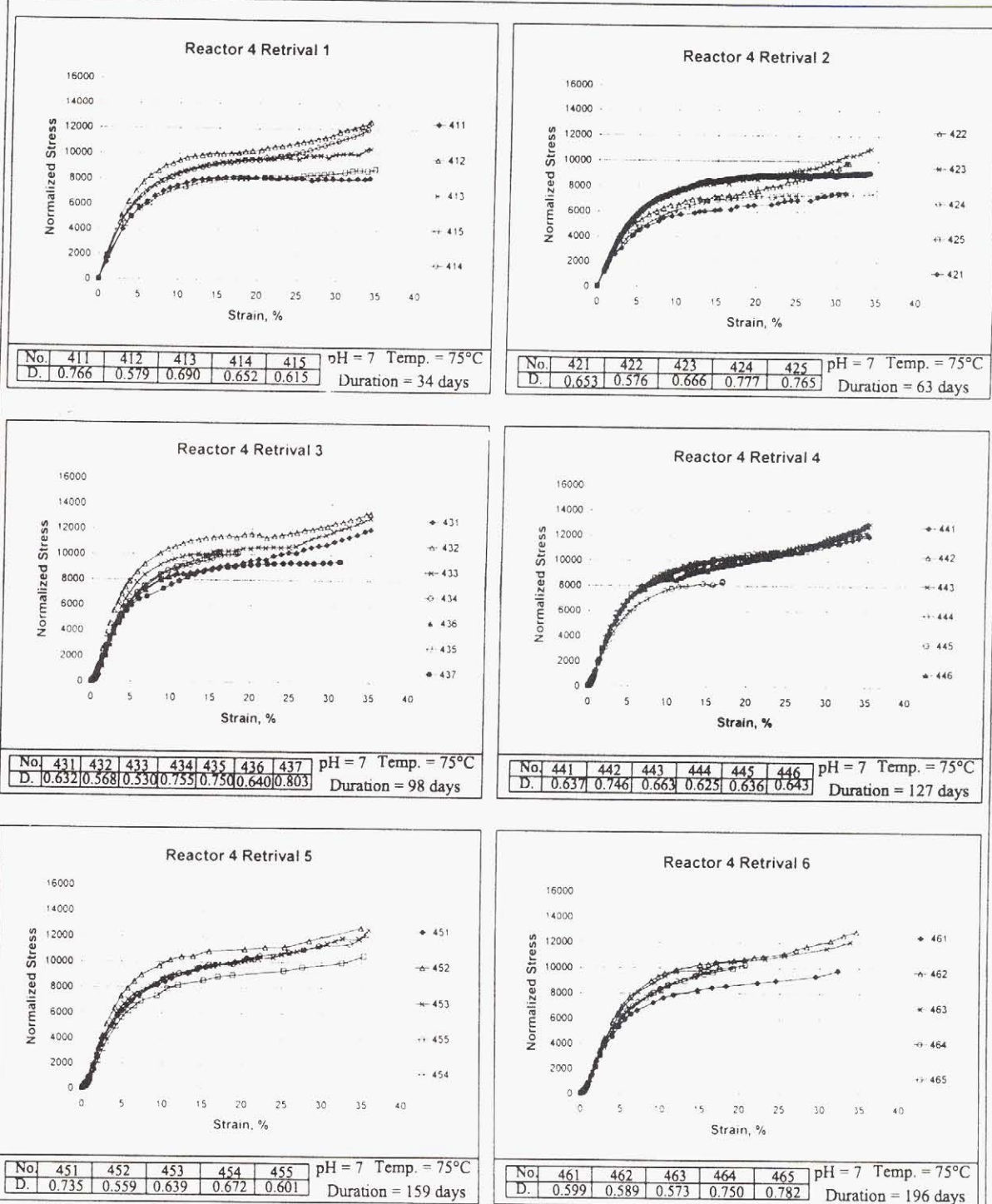
D. = Density of each specimen expressed in gm/cm<sup>3</sup>



**Fig.6-15** Stress Strain Curve for Reactor # 3 Normalized by Denisty & Location

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>

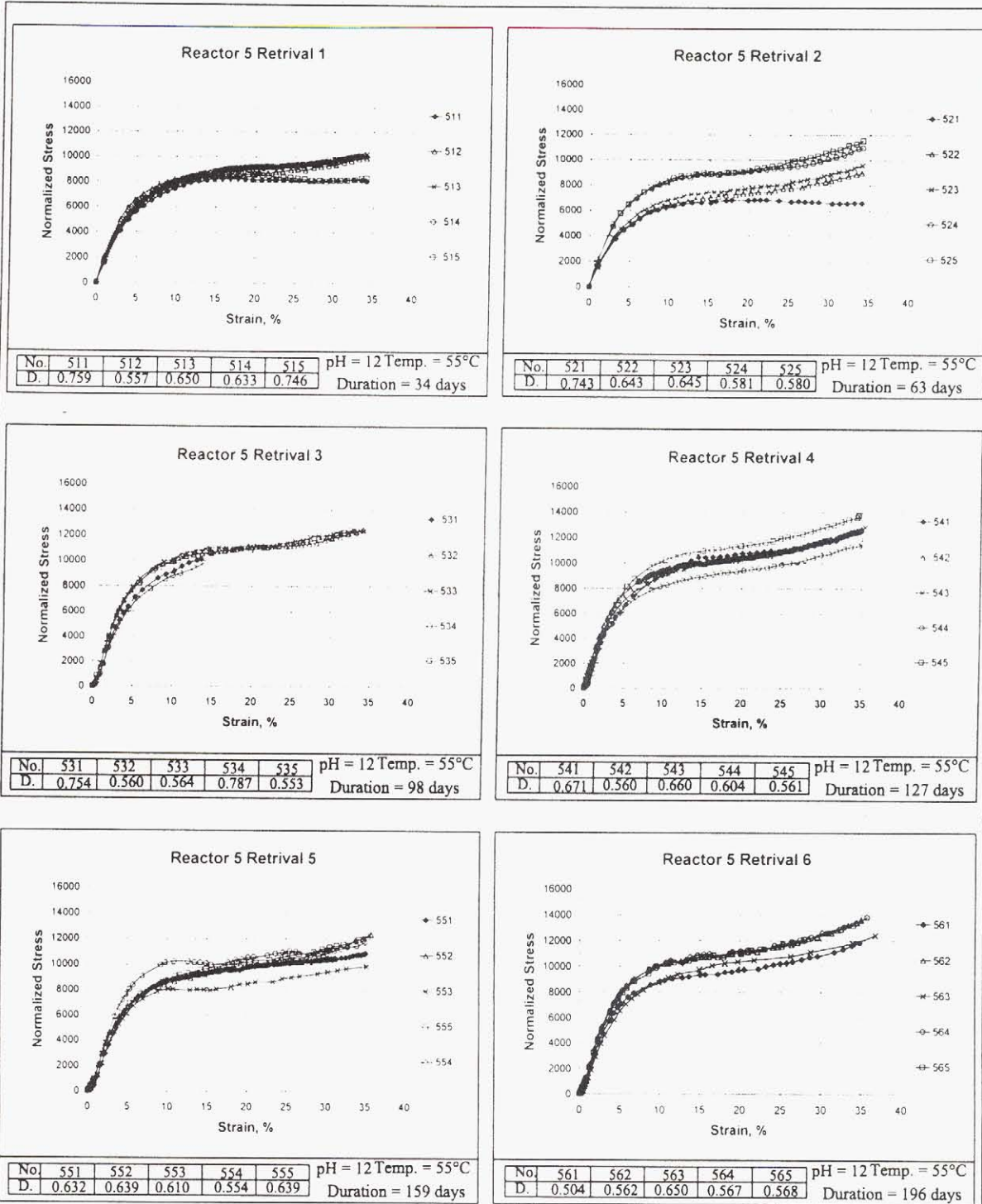


**Fig.6-16 Stress Strain Curve for Reactor # 4 Normalized by Denisty & Location**

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm3

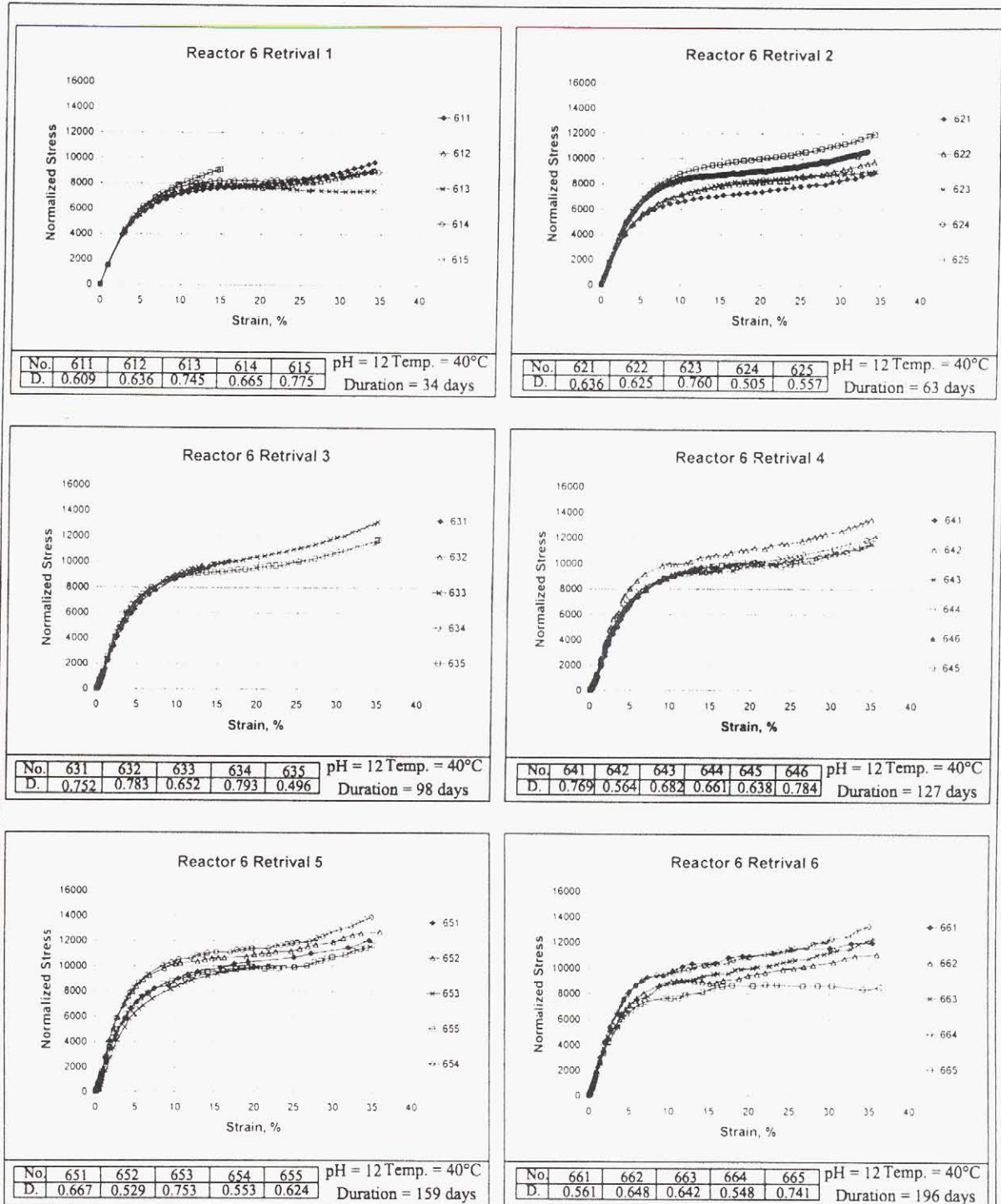




**Fig.6-17 Stress Strain Curve for Reactor # 5 Normalized by Denisty & Location**

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

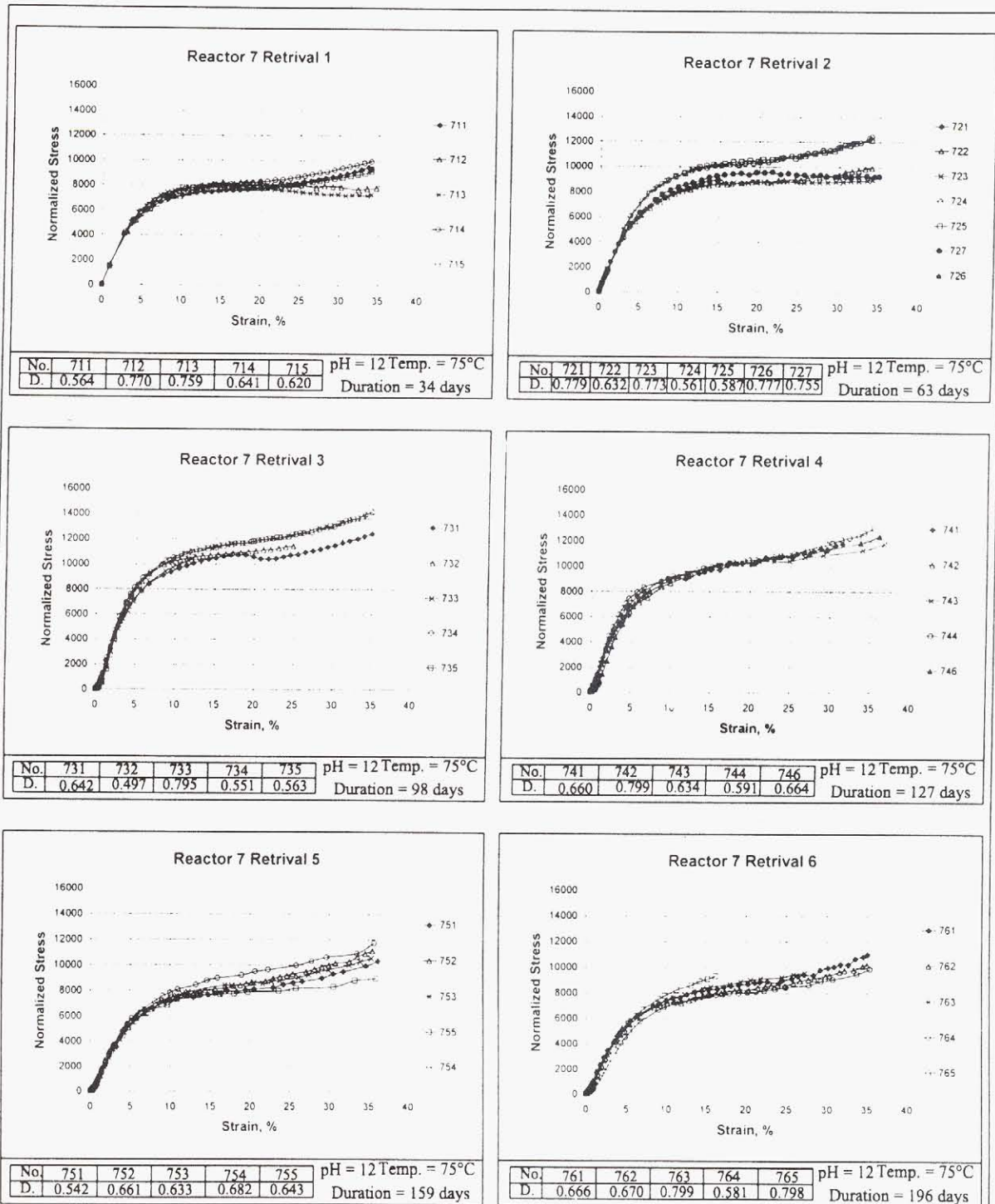
D. = Density of each specimen expressed in gm/cm<sup>3</sup>



**Fig.6-18** Stress Strain Curve for Reactor # 6 Normalized by Density & Location

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>

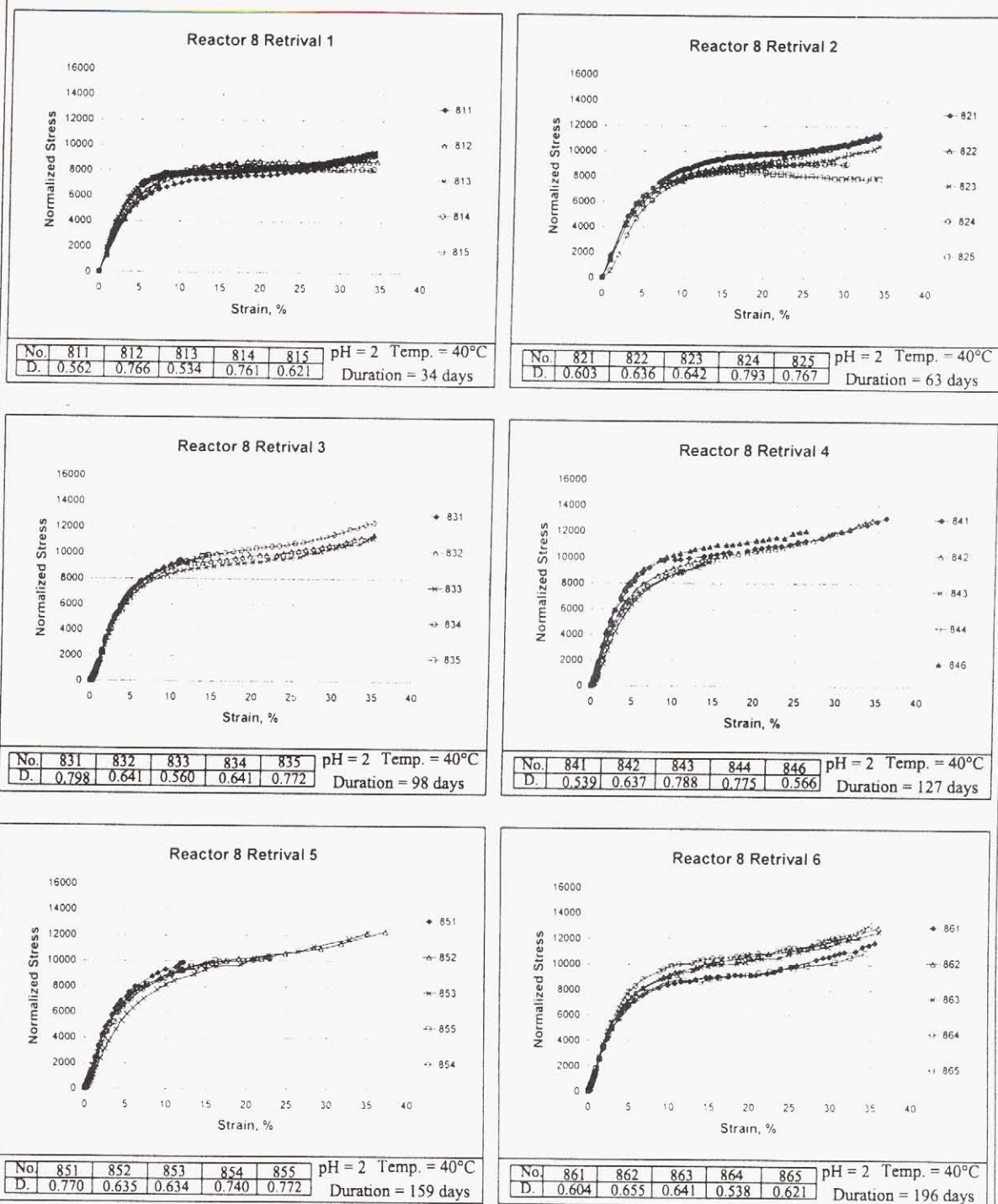


**Fig.6-19** Stress Strain Curve for Reactor # 7 Normalized by Denisty & Location

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>

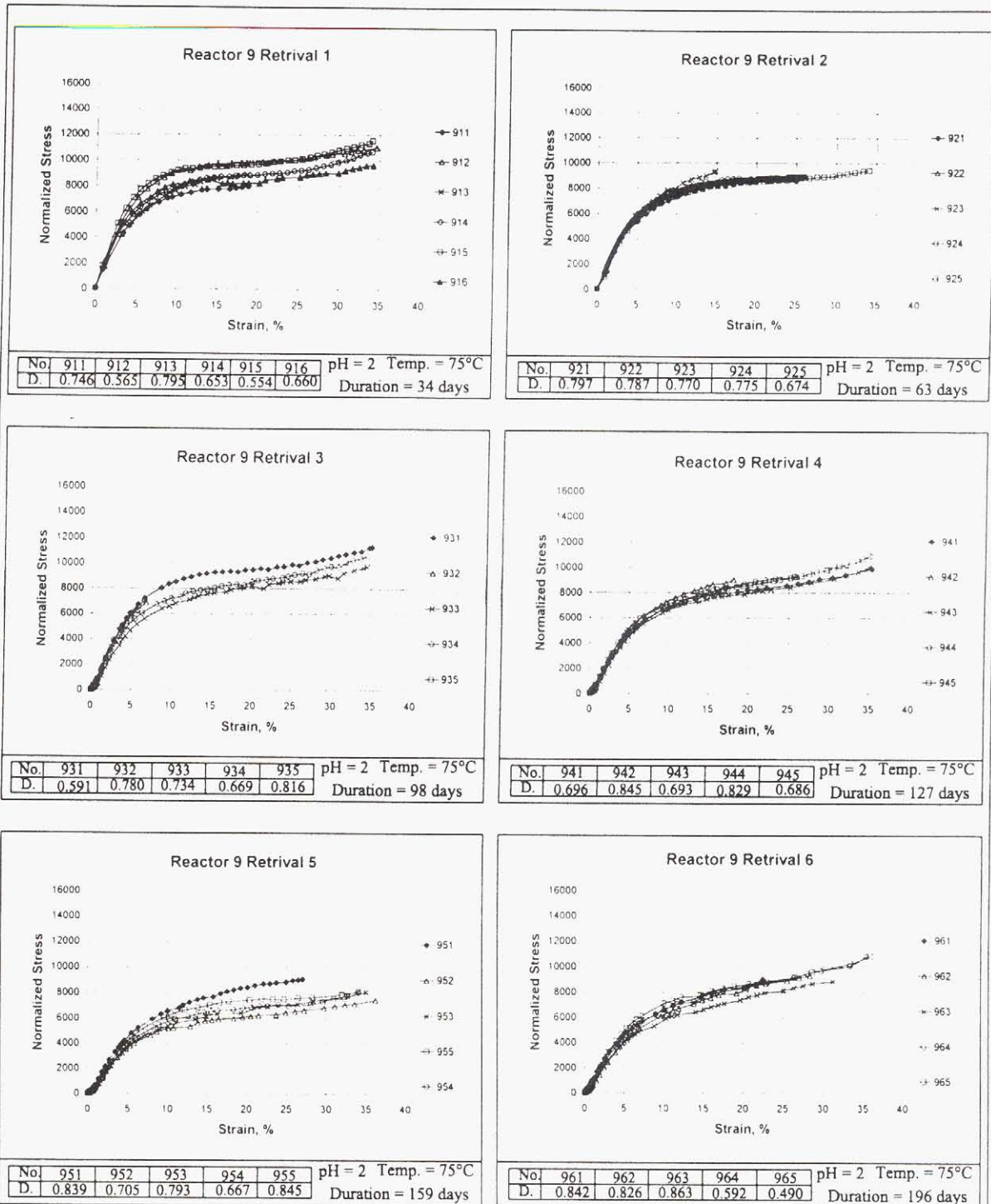




**Fig.6-20** Stress Strain Curve for Reactor # 8 Normalized by Denisty & Location

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>



**Fig.6-21** Stress Strain Curve for Reactor # 9 Normalized by Density & Location

No. = Code number assigned to each specimen the first digit from the left denotes the reactor number, the next digit denotes the retrieval number, and the last digit denotes the specimen number in the retrieval. (See appendix 1 for a complete list of all specimens characteristics.)

D. = Density of each specimen expressed in gm/cm<sup>3</sup>



# Chapter Seven

## DATA REDUCTION AND ANALYSIS

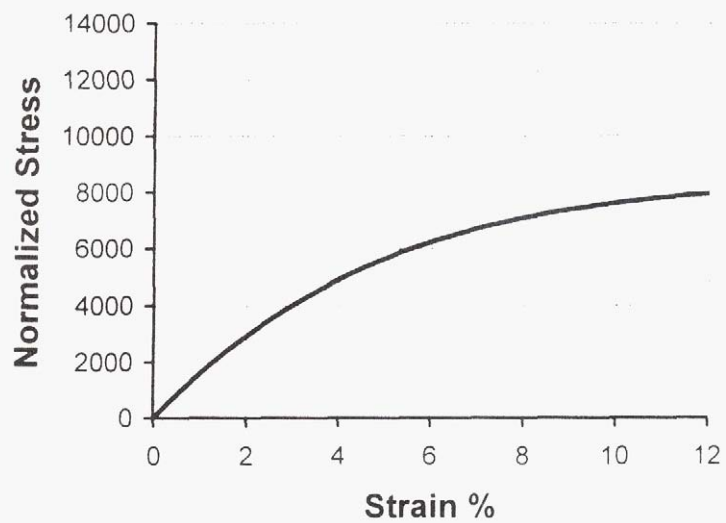
### 7.1 INTRODUCTION:

In this chapter, the data from chapter six were reduced and analyzed to evaluate the behavior of Seapile™ plastic piling in the acidic, alkaline, and neutral environments

### 7.2 DATA REDUCTION

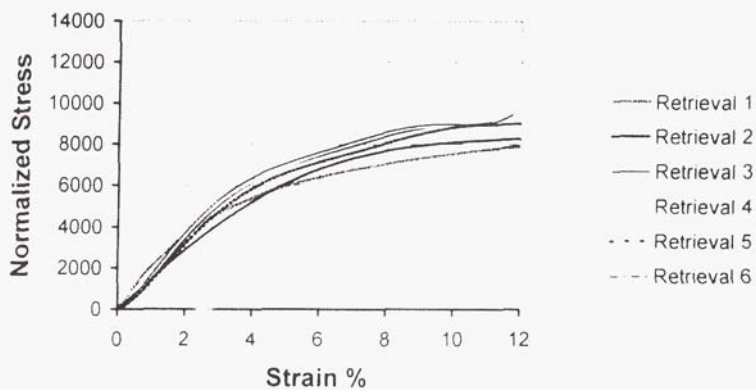
An average curve was calculated for each set of stress-strain curves obtained from each retrieval. The average curve is simply a numerical average of the characteristic stress-strain curves of all the specimens tested in any retrieval. These average curves are shown in Figs. 7-1 to 7-4. Fig. 7-1 shows the as received average curve, while Figs. 7-2 to 7-4 show the average curves for the aged specimens.

### NORMALIZED STRESS AVERAGES For As-Received Samples

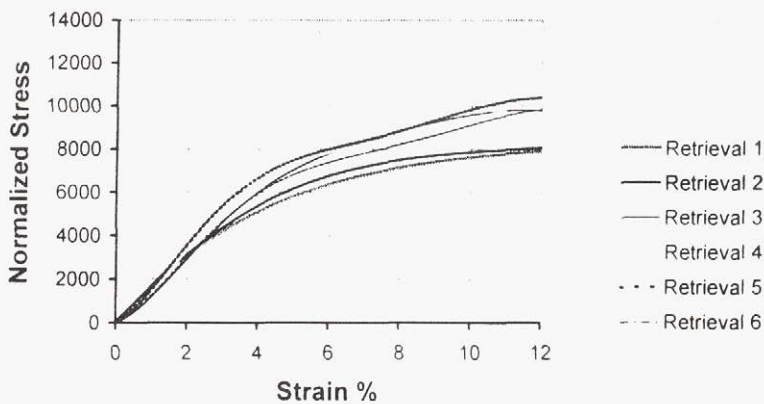


**Fig. 7-1** As Received Average Curve

### NORMALIZED STRESS AVERAGES For Reactor 8 (pH=2, Temp.=40°C)



### NORMALIZED STRESS AVERAGES For Reactor 1 (pH=2, Temp.=55°C)



### NORMALIZED STRESS AVERAGES For Reactor 9 (pH=2, Temp.=75°C)

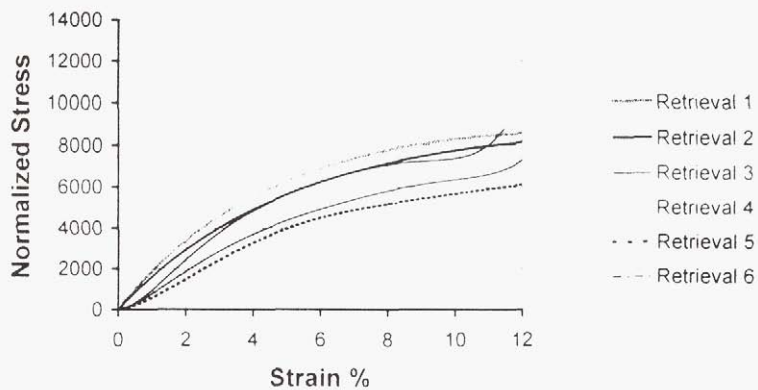
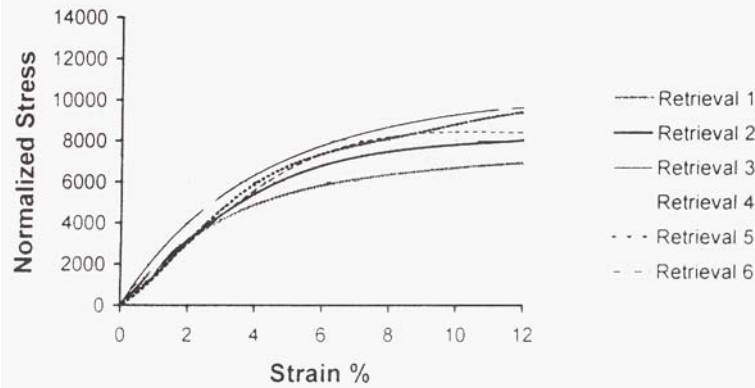
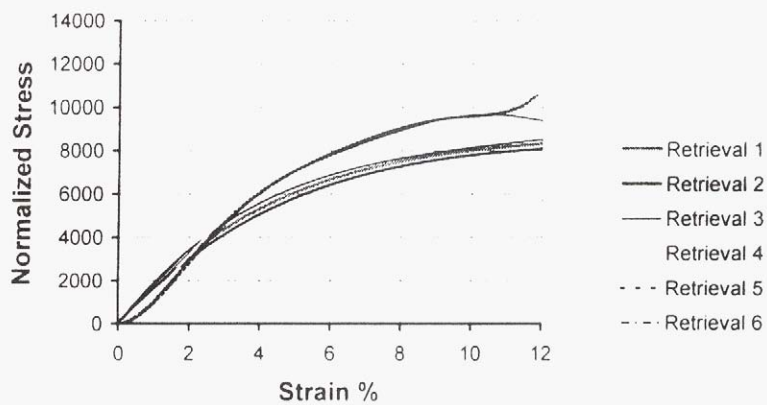


Fig. 7-2 Aged Average Curves For Acidic Environment

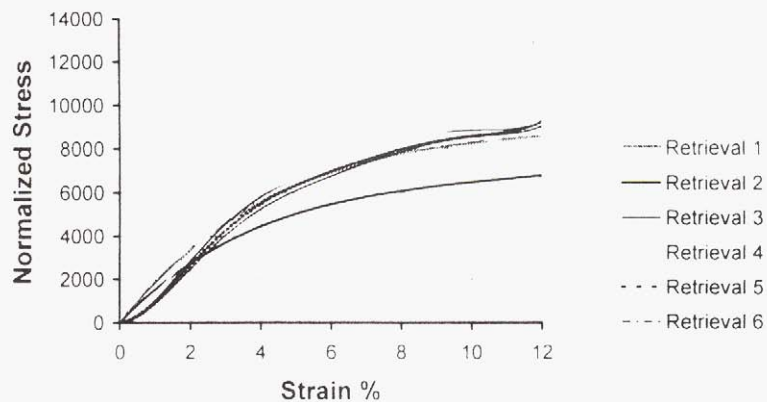
### NORMALIZED STRESS AVERAGES For Reactor 2 (pH=7, Temp.=40°C)



### NORMALIZED STRESS AVERAGES For Reactor 3 (pH=7, Temp.=55°C)

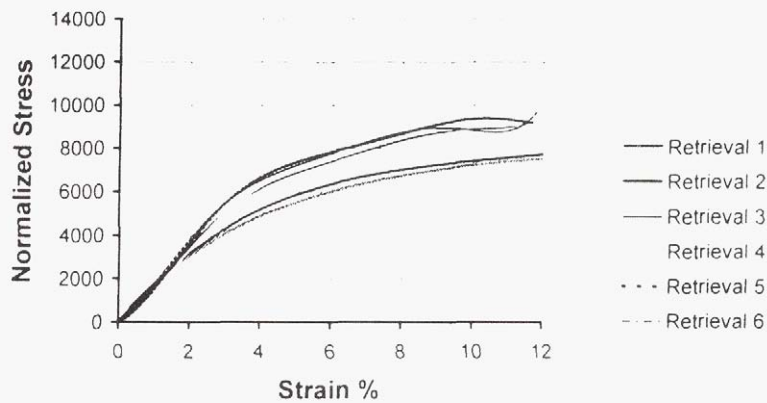


### NORMALIZED STRESS AVERAGES For Reactor 4 (pH=7, Temp.=75°C)

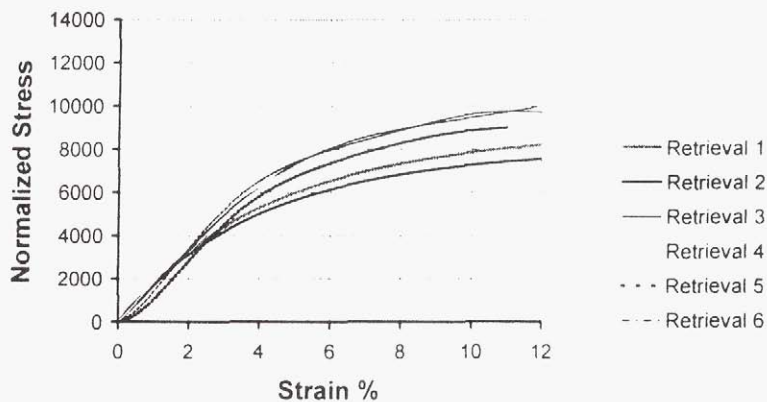


**Fig. 7-3** Aged Average Curves For Neutral Environment

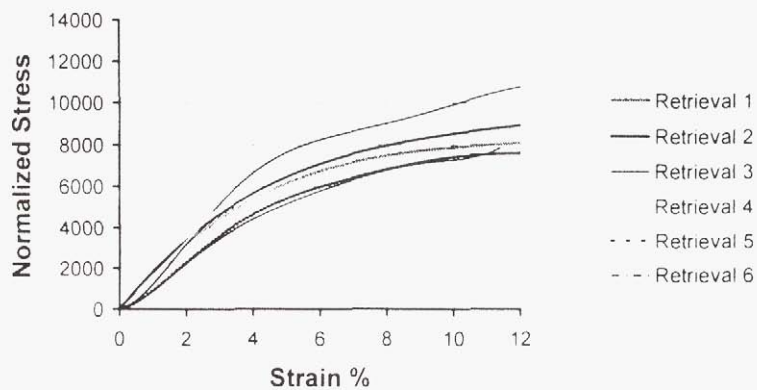
**NORMALIZED STRESS AVERAGES**  
For Reactor 6 (pH=12, Temp.=40°C)



**NORMALIZED STRESS AVERAGES**  
For Reactor 5 (pH=12, Temp.=55°C)



**NORMALIZED STRESS AVERAGES**  
For Reactor 7 (pH=12, Temp.=75°C)



**Fig. 7-4** Aged Average Curves for Alkaline Environment

### 7.2.1 Comparison Criteria

The Seapile™ plastic samples did not have a defined failure point, stress continued to increase with strain and no peak was observed. For this reason it was decided to select four representative strain % at 1%, 2%, 4%, and 8% for further investigation. These values were selected because they are the most likely to be encountered by the piles while they are in service.

Table 7-1 to 7-4 show the incubation time vs. the normalized stress for the nine reactors at the selected strain rates mentioned before. The values of the normalized stress shown in tables 7-1 to 7-4 were calculated using the equations of the average curves shown in Figs. 7-1 to 7-4. Each plot shows the degradation (or increase) in normalized strength at 3 different temperatures and the selected strain% for either acidic, alkaline or neutral environments.

Table 7-1 Incubation Time Vs. Normalized Stress Values at 1% Strain																		
Retrieval As Received	Incu Time in days	Incu Time in Hrs	Acidic Environment (pH=2)				Neutral Environment (pH=7)				Alkaline Environment (pH=12)							
			Reactor 8 Temp.=40°C		Reactor 9 Temp.=75°C		Reactor 2 Temp.=40°C		Reactor 3 Temp.=55°C		Reactor 4 Temp.=75°C		Reactor 5 Temp.=55°C		Reactor 6 Temp.=40°C		Reactor 7 Temp.=75°C	
			Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress
1	34	816	1595.53	2113.95	1595.53	1714.09	1595.53	1924.59	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	
2	63	1512	1471.68	1680.13	1595.53	1646.73	1595.53	1611.11	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	
3	98	2352	1407.18	1181.29	1595.53	2296.10	1595.53	958.41	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	
4	127	3048	1550.33	1426.75	1595.53	1677.86	1595.53	792.31	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	
5	159	3816	1341.35	1528.68	1595.53	1361.44	1595.53	1361.44	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	
6	196	4704	1550.27	1244.95	1595.53	1468.42	1595.53	774.31	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	1595.53	

Table 7-2 Incubation Time Vs. Normalized Stress Values at 2% Strain																					
Retrieval As Received	Incu Time in days	Incu Time in Hrs	Acidic Environment (pH=2)				Neutral Environment (pH=7)				Alkaline Environment (pH=12)										
			Reactor 8 Temp.=40°C		Reactor 1 Temp.=55°C		Reactor 9 Temp.=75°C		Reactor 2 Temp.=40°C		Reactor 3 Temp.=55°C		Reactor 4 Temp.=75°C		Reactor 5 Temp.=55°C		Reactor 6 Temp.=40°C		Reactor 7 Temp.=75°C		
			Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	
	0	0	2924.92		2924.92		2924.92		2924.92		2924.92		2924.92		2924.92		2924.92		2924.92		2924.92
1	34	816	3609.91	3101.32	3429.40	3168.14	3214.97	3389.29	3081.74	3262.62	3262.62	3262.62	3262.62	3262.62	3262.62	3262.62	3262.62	3262.62	3262.62	3262.62	
2	63	1512	2876.97	3127.43	2934.06	3134.02	3003.87	2755.64	3191.90	3128.68	3191.90	3128.68	3191.90	3128.68	3191.90	3128.68	3191.90	3128.68	3191.90	3128.68	
3	96	2352	3392.86	2914.58	2441.66	4020.13	3422.22	2864.45	3495.20	3368.18	3495.20	3368.18	3495.20	3368.18	3495.20	3368.18	3495.20	3368.18	3495.20	3368.18	
4	127	3048	3538.71	3312.80	2018.21	3728.48	3180.22	2894.42	3342.19	3628.32	3344.37	3628.32	3344.37	3628.32	3344.37	3628.32	3344.37	3628.32	3344.37	3628.32	
5	159	3816	3156.72	3573.60	1478.27	3082.38	2989.42	2667.65	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	2922.08	
6	196	4704	3705.24	3011.47	1859.84	2978.41	2757.35	2487.58	3850.10	2487.58	3850.10	2487.58	3850.10	2487.58	3850.10	2487.58	3850.10	2487.58	3850.10	2487.58	

Table 7-3 Incubation Time Vs. Normalized Stress Values at 4% Strain																				
Retrieval As Received	Incu Time in days	Incu Time in Hrs	Acidic Environment (pH=2)				Neutral Environment (pH=7)				Alkaline Environment (pH=12)									
			Reactor 8 Temp =40°C		Reactor 1 Temp =55°C		Reactor 9 Temp =75°C		Reactor 2 Temp =40°C		Reactor 3 Temp =55°C		Reactor 4 Temp =75°C		Reactor 5 Temp =55°C		Reactor 6 Temp =40°C		Reactor 7 Temp =75°C	
			Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress
1	34	816	4926.79	5421.96	4926.79	5109.72	4926.79	5554.52	4926.79	4926.79	4926.79	4926.79	4926.79	4926.79	4926.79	4926.79	4926.79	4926.79	4926.79	
2	63	1512	5226.40	5378.35	4909.29	5474.85	4909.29	5474.85	5069.39	4455.56	5189.13	5010.47	5662.75	5662.75	5662.75	5662.75	5662.75	5662.75	5662.75	
3	98	2352	6175.26	5989.83	4828.85	5582.17	5798.93	5582.17	5798.93	5147.81	5147.81	6638.34	6638.34	6638.34	6638.34	6638.34	6638.34	6638.34	6638.34	
4	127	3048	6216.52	6319.08	4136.71	6732.00	6202.32	6055.33	6055.33	5930.17	5930.17	6732.00	6732.00	6732.00	6732.00	6732.00	6732.00	6732.00	6732.00	
5	159	3816	5866.42	6655.38	3280.66	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	5906.29	
6	196	4704	6395.28	5940.23	3705.40	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	5612.35	

Table 7-4 Incubation Time Vs. Normalized Stress Values at 8% Strain																				
Retrieval As Received	Incu Time in days	Incu Time in Hrs	Acidic Environment (pH=2)				Neutral Environment (pH=7)				Alkaline Environment (pH=12)									
			Reactor 8 Temp.=40°C		Reactor 1 Temp.=55°C		Reactor 9 Temp.=75°C		Reactor 2 Temp.=40°C		Reactor 3 Temp.=55°C		Reactor 4 Temp.=75°C		Reactor 5 Temp.=55°C		Reactor 6 Temp.=40°C		Reactor 7 Temp.=75°C	
			Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress	Norm. Stress	Temp. Stress
1	34	816	7104.85	7074.39	7104.85	7141.74	7774.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	
2	63	1512	7677.68	7504.66	7104.85	7141.74	7774.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	
3	98	2352	8380.37	8825.70	7104.85	7141.74	7774.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	
4	127	3048	8495.80	8678.80	7104.85	7141.74	7774.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	
5	159	3816	8040.50	8855.48	7104.85	7141.74	7774.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	
6	196	4704	8578.08	8219.95	7104.85	7141.74	7774.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	7104.85	



# Incubation Time Vs. Norm. Stress For Acidic Env.

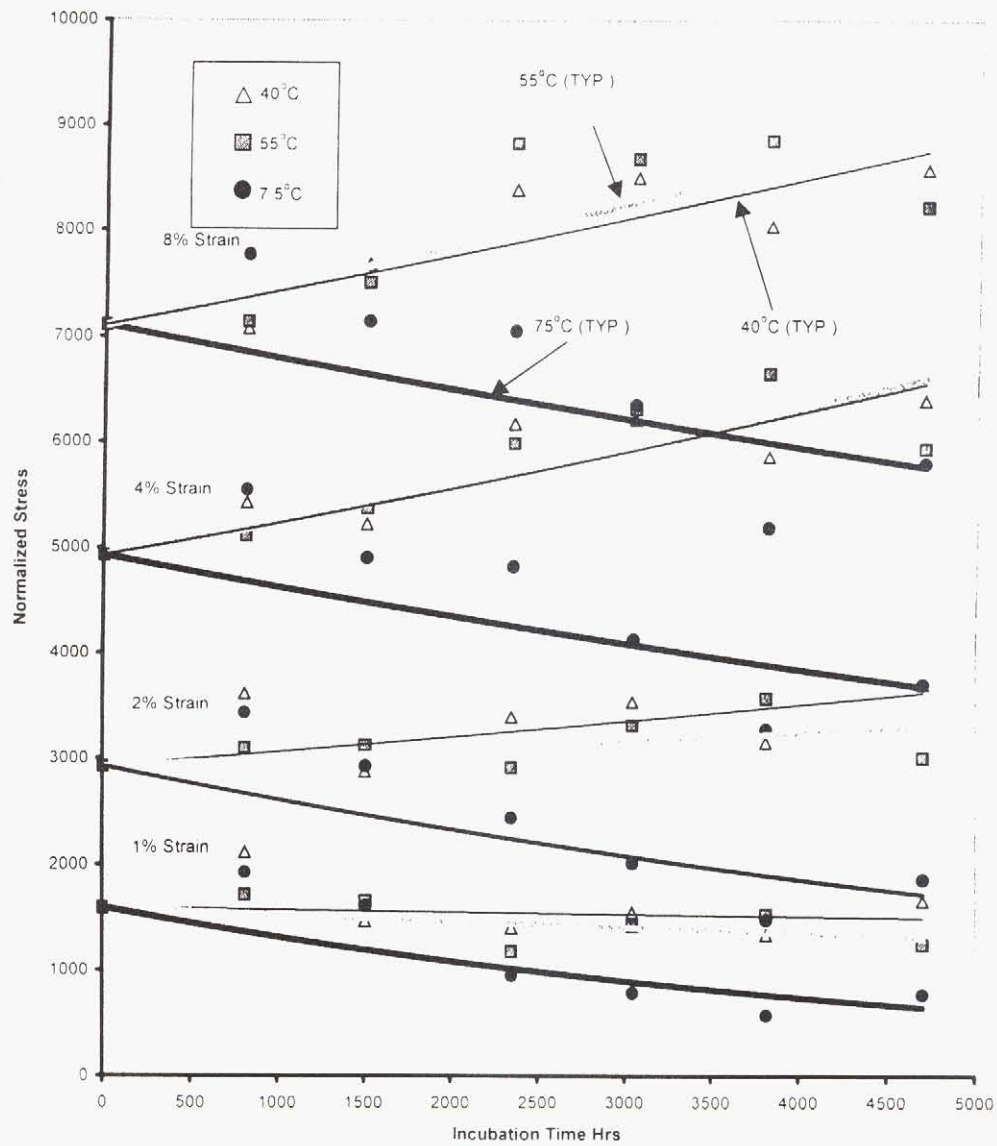


Fig. 7-5 Incubation Time Vs. Norm. Stress For Acidic Env.



# Incubation Time Vs. Norm. Stress For Neutral Env.

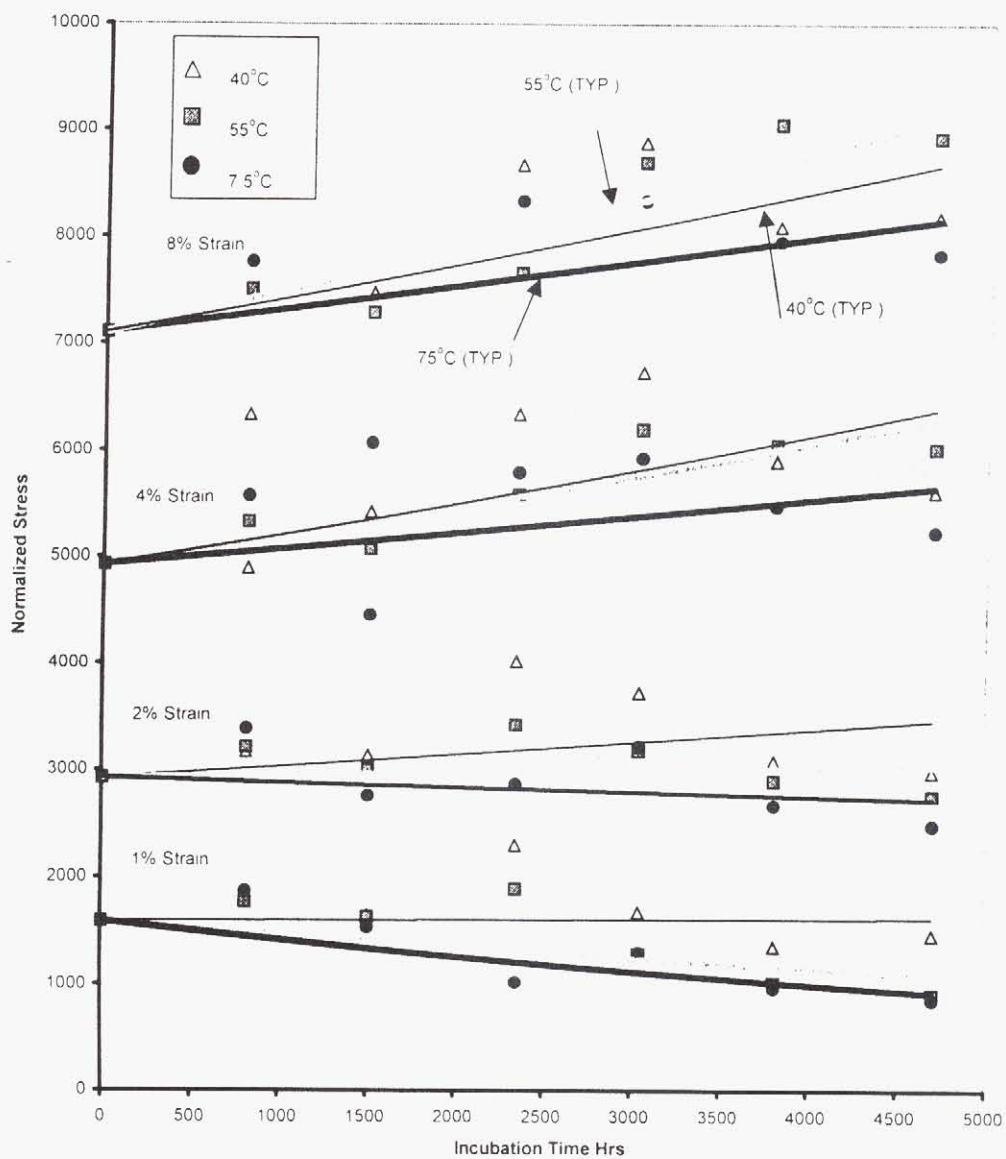


Fig. 7-6 Incubation Time Vs. Norm. Stress For Neutral Env

### Incubation Time Vs. Norm. Stress For Alkaline Env.

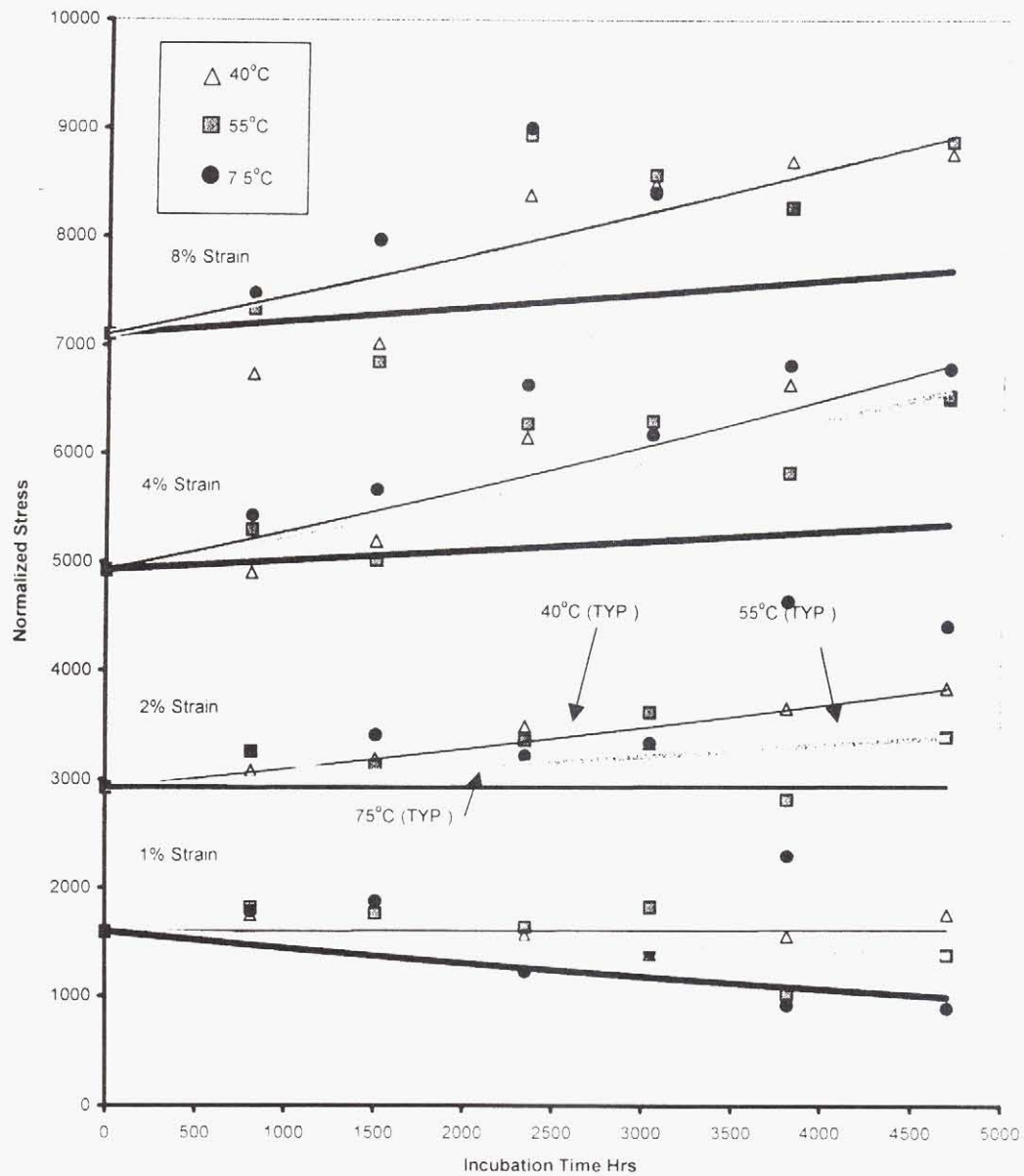


Fig. 7-7 Incubation Time Vs. Norm. Stress For Alkaline Env

### 7.3 DATA ANALYSIS

One of the main assumptions involved in the Arrhenius modeling is that the materials behavior at the high temperature incubation range is constant within this range and can be extrapolated to the lower temperature behavior of practical interest, (Koerner et al 1992). Most of the results violated this requirement and gained strength particularly at high strain. This can be illustrated for the 2%, 4% and 8% curves in Figs. 7-5, 7-6, and 7-7 that indicate that the material has gained strength with time, except for the highest temp in the acidic environment. A reduction of strength was noted for the 1% strain curves only.

The strength gain associated with the high strain % could be caused by the thermal stress hardening of the material due to thermal closure of micro-cracks. It appears that micro-cracks closure influence the strength at higher strains only. At 1% strain the stress hardening was not observed.

From the data analysis it appears that only the acidic environment with high incubation temperature (75°C) has a high degradative effect on the material. Hence, Arrhenius modeling could be implemented to predict the time needed to achieve a certain strength loss at lower in service temperature for the acidic environment only.

Accordingly, based on the Arrhenius modeling assumption stated above only the graphs at 1% strain could be used to construct the Arrhenius plot. Fig. 7-8 shows the five Arrhenius plots for the acidic media at 1% strain for 95,90,85,80,75 % remaining strength. These Arrhenius plots were constructed following the steps explained in chapter four.

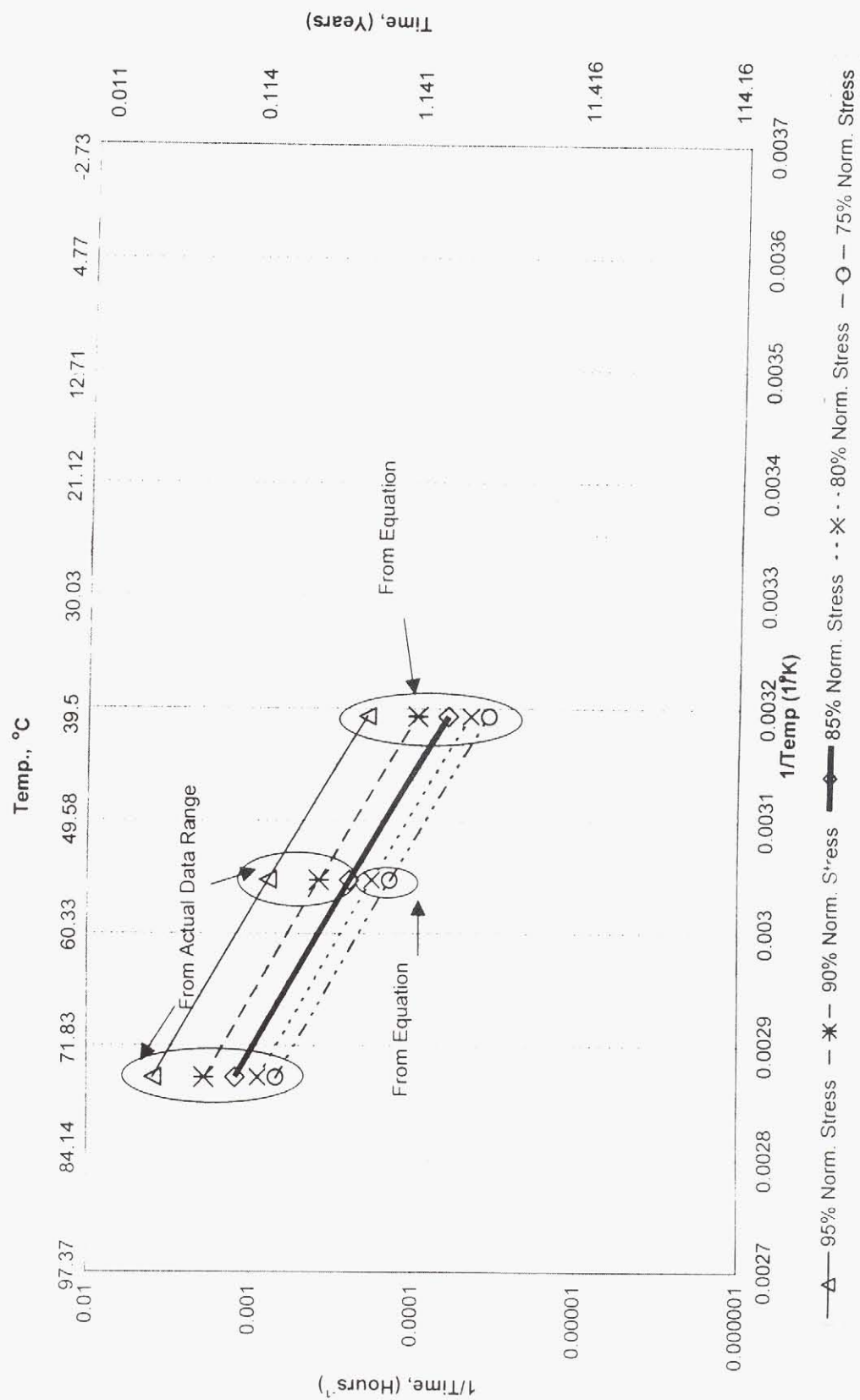


Fig. 7-8 Arrhenius Plot for Different Percentages of Retained Norm. Stress @ 1% Strain

The in service temperature selected for calculating the remaining strength was 25°C. Fig. 7-9 shows the relation between the time in years and the remaining strength. This curve was calculated using the Arrhenius plots shown in Fig. 7-8. This was done by extending the straight lines until they meet with the 25°C temp. (298 K), then reading the corresponding time on the y-axis.

The same plot could not be done for the alkaline and neutral environments, simply because there is only 2 curves, the 75°C and 55°C that show strength loss, (see Figs 7-6 and 7-7). From these 2 curves we can get 2 points on the Arrhenius plot which was considered as insufficient number of data points to extrapolate the results.

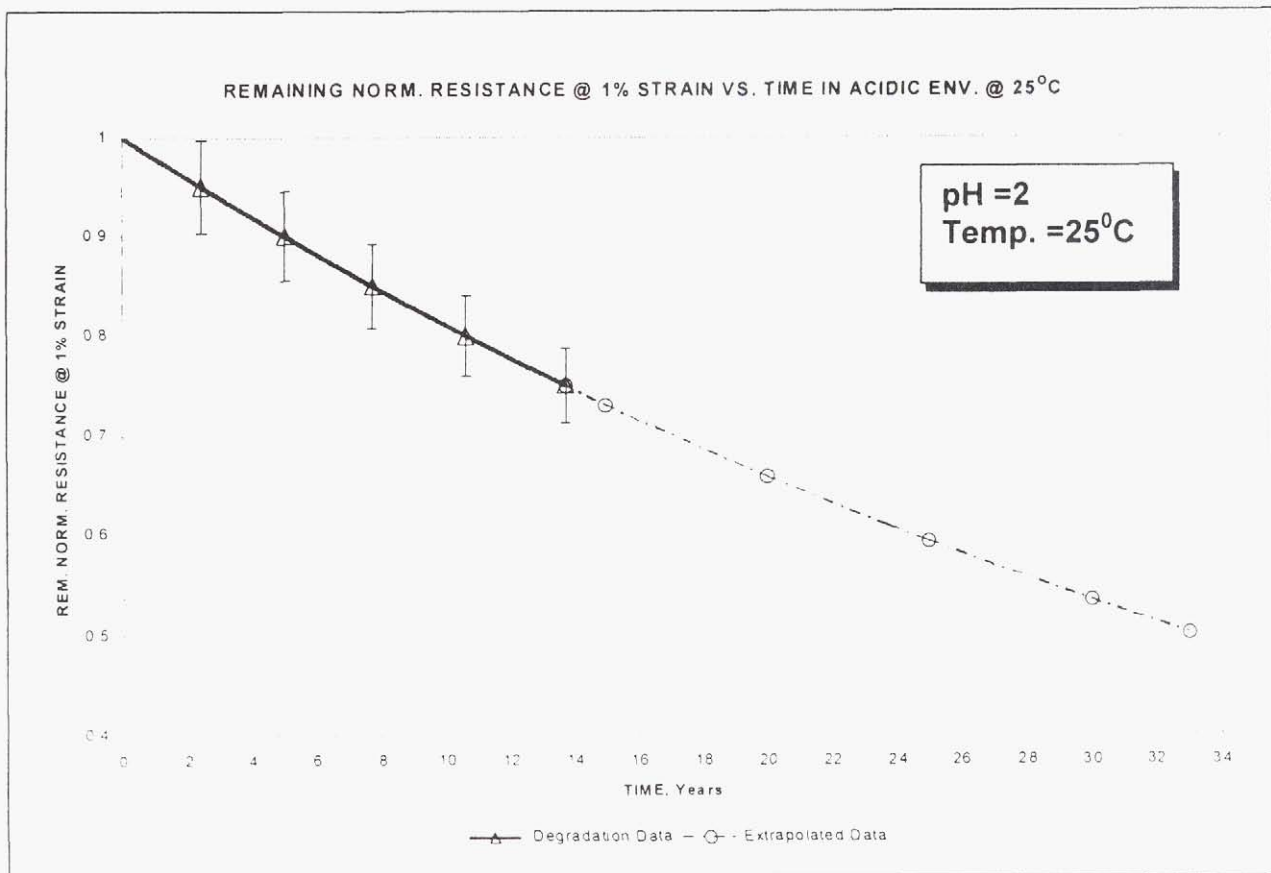


Fig. 7-9 Remaining Normalized Resistance @ 1% Strain in Room Temperature

# Chapter Eight

## CONCLUSIONS

Piling material made of fiber reinforced polymer (FRP) and/ or fiberglass has been developed in the last 10-15 years. These materials offer performance advantages for use in aggressive and marine environments. So far, composite piling has been used primarily in marine fendering applications and light bearing applications. The existing composite piling materials offer a number of advantages and disadvantages. Advantages include durability and environmental dividends. Disadvantages include high cost, less efficient drivability, high compressibility, and lack of a long-term track record.

### 8.1 OBJECTIVES & SCOPE OF THIS RESEARCH

The objective of this project was to assess the durability of piling made of recycled plastics in aggressive soils for long term usage in civil infrastructure application. This required the development of accelerated tests permitting prediction of the behavior of the plastic piles in actual use, within the short duration of this project.

In order to simulate the aggressive soil environment in the lab, aqueous solutions were used since it is simpler to control.

To assess the influence of pH of the environment on the rate of mechanical degradation the following environments have been selected:

- Neutral environment of water with pH=7
- Acidic environment of aqueous solution of  $\text{H}_2\text{SO}_4$  at pH=2
- Alkaline environment of aqueous solution of NaOH at pH=12

For achieving measurable changes of strength, within the limited laboratory time, the samples were aged at elevated temperatures (40, 55, & 75°C). Coupon specimens were subjected to the three prescribed environments at these three elevated temperature (9 reactors). Specimens were retrieved monthly from each reactor. Each retrieval contained at least five specimens for testing in unconfined compression, per ASTM D 695.

### **8.1.1 SCOPE OF STUDY**

The scope of this research is limited to the laboratory investigation of the accelerated degradation of Seaward International piling samples only (Seapile™). The experimental program is intended as an empirical investigation of the effects of specific environmental variables on the degradation process, if any, of the Seapile™ specimens. The product's service life is also estimated with respect to being exposed to that specific aggressive media using the Arrhenius model.

The scope of this study is by necessity limited in that:

Commercial plastic piling products are not well characterized, and generally contain residues and additives that can affect the chemical degradation

mechanism. These additives and residues can make degradation more complex by causing secondary reaction to occur.

- To achieve measurable mechanical changes during the limited laboratory time only severe conditions of treatment, as compared to the in-service conditions, are used to accelerate degradation.
- The plastic piling specimens are made of recycled plastics only.

Unconfined compression testing of cylindrical 0.5 x 1.0 inches was used to assess the strength loss of the plastic piling samples, according to ASTM D-695. Due to variability of plastic, ASTM D-695 requires that at least 5 specimens be tested in order to get an average data point.

The unconfined compression testing is considered to be an index test for establishing relative data for comparison reasons and not for assessing the strength of the material.

In order to reduce the data scatter, five different methods were investigated to normalize the stress strain data in full

- Normalizing the stress (kg/cm<sup>2</sup>) by the weight of the specimen.
- Normalizing the stress (kg/cm<sup>2</sup>) by the density (kg/cm<sup>3</sup>) of the specimen.
- Normalizing the force (kg), by the the weight (kg) of the specimen and plotting the result against the strain(%).
- Normalizing the stress by the non dimensional term  $\sigma/\gamma D$ , where:-

$\sigma$  = stress psi

$\gamma$  = density pci

D = diameter of specimen (0.5 inches)

- Normalizing the stress by the non dimensional term  $\sigma/\gamma R$ , where:-

$\sigma$  = stress psi



$\delta$  = density pci

R = radial distance from center of Seapile™ to center of specimen

The last method from the previous list was adapted for all the test results, since it resulted in the least data scatter.

## 8.2 RESEARCH CONCLUSIONS

The 6 months 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:

- Only the acidic environment (pH=2) had a considerable degradation effect on the Seapile™ samples.
- Thermal Stress hardening was noticed for most of the specimens, which is thought to be caused by the closure of the hair cracks
- The Arrhenius modeling could only be used in low compression strains where the stress hardening of the material, was not noticed.
- At a severe acidic environment (pH=2) an estimated 25% (+/-5%) loss in resistance at 1% strain, of the coupon specimens extracted from Seapile™ cores takes place in about 14 years. The half-life (50% loss +/- 5%) is estimated to occur in 33 years.

- It has to be noted that the specimens were punched out from the core of the Seapile™ product. The material that is surrounding the core is much denser material with a better quality, specially at the edges, which may further the delay of the degradation process
- Arrhenius model estimates are based on results obtained under conditions of intensive stirring of aqueous media which intensifies the degradation action. Therefore, all calculations of strength loss should be considered as a conservative estimate for the degradation rate for in-use condition. The Seapile™ product is expected to exhibit less degradation in civil engineering applications.

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