Recent Developments in FRP Composite Piling Practice

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by

Magued Iskander, PhD, PE,
Associate Professor, Polytechnic University,
6 Metrotech Center, Brooklyn, NY 11201
Phone: (718) 260-3016
Fax: (718) 260-3433
Email: Iskander@poly.edu

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Magued G. Iskander, PhD, PE

Magued Iskander, PhD, PE, Associate Professor, Polytechnic University, 6 Metrotech Center, Brooklyn, NY 11201

Abstract. The deterioration of concrete, steel, and timber is a serious hindrance to construction in marine and corrosive environments. Composite materials such as fiber-reinforced polymers (FRP) can offer performance advantages for construction in these environments. In the last decade, piling made of FRP composites has been used experimentally throughout North America. However, composites face obstacles because they do not have a long track-record of use in civil engineering structures. A comprehensive review of the current experience in research, testing, design, and practice of composite piling is presented in this paper.

INTRODUCTION

The deterioration of concrete, corrosion of steel, and marine borer attacks on timber piling systems are serious hindrances to waterfront construction which cost the United States nearly $1 billion annually for repair and replacement *(1)*. The Federal Water Pollution Control (*clean water*) Act of 1972 gradually rejuvenated many of the nation's waterways and harbors. With the return of the marine life, tiny marine borers flourished, attacking the timber piles (Fig. 1), which support many of the nation's harbor piers *(2)*. At the same time, approximately 3.3 million tons of rigid plastic containers are landfilled annually in the United States *(3)*. The use of recycled plastics to manufacture composite piling products is advantageous for two reasons. First, it utilizes plastics, which would have been otherwise landfilled. Second, the use of composites in aggressive environments can be more economical when life-cycle costs are considered *(4)*.

FRP Composite piling has been used to a limited degree, or experimentally, in a number of ports and waterfront facilities. Most FRP piling is used for fendering applications, however it has also been used to support a few piers. For example, Tiffany Street Pier in New York City was constructed entirely from recycled plastics. Recycled plastic pins have also been proposed for slope stabilization *(5)*.

Several barriers must be overcome for FRP composite piling to be accepted on a widespread basis. First, economic necessity requires FRP piling to be cost-competitive on a life cycle basis *(6)*. Second, mechanical and physical properties should be defined and long-term performance should be verified under field conditions *(7)*. Third, design methods for predicting driveablity and capacity should be developed *(8)*. Fourth, design and testing standards should be developed *(9)*, and fifth, several piles should be instrumented, installed, load tested, and monitored.

This paper presents a comprehensive review of the state of the practice in FRP composite piling in summer 2001. Emphasis is given to available products, material properties, structural performance, durability, and driveability. The technical and economical viability of composite piles is also discussed.

DETERIORATION OF CONVENTIONAL PILING MATERIALS

Timber

Prior to the clean water act of 1972, marine borers could not exist due to pollution. One trade-off to this environmental benefit is a significant increase in marine borer activity in coastal waters, resulting in widespread damage to marine timber infrastructures (Fig. 2). Teredo, Bankia, and Limnoria are the three most common and destructive borers. Teredo and Bankia (ship-worms) enter the wood as a larva and follow the grain, tunneling deeper as the worm grows. Numerous tunneling in a timber pile make the wood's interior as holed as Swiss cheese (Fig. 3). Limnoria nibble at the outside edges of the timber piles causing timber piling to lose up to 1 inch in diameter yearly (Fig. 1). The most effective method of reducing marine borer attack is the pressure treatment with creosote and arsenate. However, treatment doesn't stop borers from attacking the wood completely.

Steel

The major cause of deterioration of steel piles is corrosion, especially in industrial and marine environments (Fig. 4). The rate of corrosion in regular soils is approximately 0.03 mm per year; it increases to 1.2 mm per year in the splash zone *(11)*. Corrosion of the steel piles can be prevented by coatings containing heavy metals, but these treatments are harmful to the environment.

Concrete

The most destructive agents for reinforced concrete piles are sodium and calcium chlorides. These salts penetrate through the concrete cracks to the reinforcing steel and form an electrical current, which causes the reinforcement to corrode. This corrosion process is accompanied by expansion, which tends to induce high tensile stresses in the surrounding concrete causing cracking and spalling (Fig. 5). In marine environments, in addition to salts, the variation of temperature, freezing and thawing, further degrades the concrete.

HISTORICAL BACKGROUND

The first proto-type recycled plastic pile was driven at The Port of Los Angeles in April, 1987 *(12)*. 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.) segments was connected by a threaded coupling. These piles suffered from delamination of the plastic shell from the steel core, However piles presently produced are warranted against delamination *(13)*.

Over the next few years, several vendors produced a variety of piling products made of virgin, recycled, and hybrid composites.

AVAILABLE PRODUCTS

In Summer 2001, a number of manufacturers were marketing composite piling products. The majority of available products are produced as a replacement for timber piling. Most composite piling products are made of fiberglass or high density polyethylene (HDPE) with fiberglass or steel reinforcement. The produced piling products are often non-homogenous and exhibit anisotropic viscoelastic behavior. Although many manufacturers advertise that their products can be used for bearing and structural applications, so far most of these products have been used in fendering applications only.

Steel Core Piling

Steel core piling was the first plastic piling product on the American market. The piles consist of a recycled plastic shell encasing a steel pipe core (Fig. 6). The steel pipe core provides all of the structural strength. 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 thicknesses ranging between 6 and 40 mm (0.237–1.594 in.) *(14)*. Plastic Piling Inc. is currently the only manufacturer of steel pipe core piling.

Reinforced Plastic Piling

These piles typically consist of an extruded recycled High Density Polyethylene (HDPE) plastic matrix reinforced with fiberglass or steel rods (Fig. 6). Additives are used to improve mechanical properties, durability, and ultraviolet (UV) protection. Polymer based resins are heavier than wood and foaming of the resin is used to make the product lighter. The matrix may also contain a small percentage of fiberglass to enhance its physical properties. 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 diameter between 25 and 36 mm (1–1.41 in.) *(14, 15*). Seapile™, which is a product of Seaward International, uses approximately 800 recycled one-gallon milk jugs per linear meter.

Fiberglass Pipe Pile

Fiberglass pipe piles typically consist of an acrylic coated fiberglass tubular section filled with concrete. The fiberglass (glass/vinyl ester) shell provides structural strength, and the acrylic coating protects the pile against abrasion, ultraviolet, and chemical attacks. Hardcore and Lancaster Composites produce piles of this type under the commercial names FTP™ and CP40, respectively *(16, 17)*. Hardcore piles are typically filled with concrete, after the installation in order to improve their structural performance. Lancaster composites CP40 piles are filled with concrete and cured, prior to driving. 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 thicknesses, in any shippable length.

Plastic Lumber

Fiber reinforced plastic piling consists of a recycled plastic matrix with randomly distributed fiberglass reinforcement in the matrix. US Plastics is currently the only manufacturer of this product. It produces a variety of structural members that conform to lumber industry standards. The product 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). Piling is available in 25 cm (10 in.) diameter with in a standard length of 7.5 m (24 ft.), but longer lengths could be custom made in any transportable length.

Wood Composites

Several wood composites exist including timber piling encased in fiberglass, and extruded mixtures of wood cutting and polymers. Typically wood composites are available in sections smaller than 30 cm in diameter/width and come in lengths up to 6m (20 ft)

STRUCTURAL BEHAVIOR

FRP composites usually have low stiffnesses which is advantageous in fendering application, where steel and concrete are considered too stiff (Table 1). However, for bearing applications, low stiffness may cause differential settlement and may adversely affect the performance of the structure. Additionally, the composite modulus of FRPs is both time and load dependent, which may result in creep, and the possibility of time dependent load shedding.

The physical and engineering properties of most polymeric piling typically exhibit a high coefficient of variation, particularly when recycled plastics are used *(18)*. For example, the unit weights of specimens taken from a Seapile™ reinforced plastic pile made by Seaward International are shown in Fig. 7. This difference in densities is caused by the manufacturing procedure of Seapile™. Seapile™, like many polymeric structural members is foamed at the center and solid at the edges. In addition, the manufacturing process could have resulted in variation in strength of the parent material across the cross section.

When the stress vs. strain data of the specimens shown in Fig. 7 were first plotted, a large scatter was observed (Fig. 8) even though the specimens came from the same pile. Several methods to normalize the data and reduce scatter were investigated *(18)*. The non-dimensional term $\sigma/\gamma R$ was found to reduce scatter the most (Fig. 9). Where σ is the measured stress, γ is the density of the specimen, and R is the radial distance from the center of the core to the location of the specimen. The term $\sigma/\gamma R$ is referred to as the *Characteristic Stress,* and is believed to be a unique signature property for foamed structural members. In any case, better definition of performance can be achieved if appropriate quality control measures are implemented.

DURABILITY

Virtually no information related to the durability of plastics in water front piling is available. Applications such as plastic piles require service lifetimes of 100+ years. Accordingly, degradation of polymeric materials buried in soils is an important concern due to their lack of a long term track record. The degradation of recycled polymers in aggressive conditions depends on the molecular structure, the presence of additives, and the presence of contaminants commonly found in recycled plastics. Most plastic piles used in construction contain additives and stabilizers, which improve the resistance of the polymers to degradation. However these additives can be susceptible to leaching or to biological attack thereby leaving the plastic pile material unprotected.

Environmental conditions which contribute to chemical degradation in polymeric materials include elevated temperature, UV radiation, exposure to oxygen, moisture, and acidic or basic environments. Salman *et al. (20)* identified the main mechanisms that degrade polymers as either hydrolysis for polyester-based materials or thermo-oxidation for polyolefin-based materials.

Hydrolytic Degradation

Hydrolysis occurs when positively charged hydrogen ions (H^+) in acidic or negatively charged hydrogen ions (OH^-) alkaline media attack the ester linkage thus breaking the polyester chain. This reduces the polymer chain length and alters its molecular weight distribution, which directly impacts the strength of the material. In addition to chain breakage, hydrolysis in alkaline media causes surface erosion of polyesters, which is manifested by weight loss. The rate of hydrolysis is slow at ambient temperatures, but is not negligible considering the typical lifetime of a civil engineering structure. Accordingly, hydrolysis may affect fiberglass piling and reinforcement, which is typically made of glass/vinyl ester *(21)*.

Thermo-Oxidation Degradation

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. Chain breakage and the associated reduction of strength of polyolefin based materials depends on the presence of oxygen as well as temperature. The rate of thermal oxidation is slow in ambient temperatures, but not negligible considering the expected life of a civil engineering structure.

Durability of Recycled FRP Composite Piling in Aggressive Environments

Iskander et al *(22)* carried a one year accelerated degradation program of Seapile™ reinforced plastic piling made of recycled plastics. The program involved high temperature incubation of coupon specimens in aqueous solutions having pH = 2–12. Unconfined compression was used as an index and approximately 700 compression tests were performed. Specimens did not exhibit a defined failure point so peak strength was defined at 10% strain.

Exposure to the acidic environment (pH =2) and alkaline environment (pH = 12) had a consistent measurable degradive effect on recycled HDPE (Fig. 10). An estimated 25% loss in resistance at 10% strain, is projected to take 21 years for coupon specimens incubated at pH = 2 and 25 years for coupon specimens incubated at pH = 12. If the reaction rates remain constant, 50–60 years are required for a 50% loss in relative compressive strength of coupon specimens under the same conditions. These projected remaining resistances are relative to specimens incubated in water and ignore the effect of aging on the mechanical properties of polymers. These results represent a lower bound because the study was conducted on coupon specimens, which were exposed to aggressive media at the surface. Piling is typically 25-40 times larger in diameter than the tested specimens.

DRIVEABILITY

The feasibility of driving FRP composite piling was studied for the typical water front site shown in Fig. 11. The soil properties indicated in Fig. 11 are typical of those properties supporting many of the New York harbor piers. Older piers are supported using timber piling. Because of marine borers' attack, new structures are supported on higher capacity piles made of steel and concrete, which allow for longer deck span distances. Nevertheless, low capacity piles are still widely used as fenders to protect piers from ship impact. Two pile capacities were selected to accommodate the range of pile capacities being used in the New York waterfront.

The driveablity of all piles was studied using GRLWEAP *(23)*. The values of pile damping and modulus correction factors determined by Iskander et al *(24)* for FRP piles were used. Soil parameters and pile properties of conventional piles were taken per PDI *(23)*. The material properties of all piles are shown in Table 1. All piles were driven closed ended, with the cushions recommended by the hammer manufacturers. Residual stress analysis was used for all piles.

The driving criteria was to install the piles at their estimated geotechnical capacity in fewer than 100 blows per foot at the end of driving. For steel and concrete, allowable driving stresses were taken as per AASHTO *(25)*. In the absence of any guidelines, the allowable driving stresses were taken as the ultimate stresses for fiberglass and recycled HDPE (Table 1).

Low Capacity Short Piles (21 tons)

The driveablity of reinforced plastic piling and fiberglass piling (driven empty) was compared to timber piling. The geometric properties of all piles are shown in Table 2. An 18.3 m (60 ft) long skin-friction pile having a nominal ultimate geotechnical capacity of 206 kN (21 tons, 42 kips) was selected. End bearing was calculated according to NAVFAC DM 7 (25) as 39 kN (8 kips) and skin friction was calculated as 167 kN (29 kips). The calculated capacity is shown ± 10% on Fig. 10 as the estimated geotechnical capacity.

The bearing curves of piles analyzed using single acting VULCAN 02 hammer having a rated energy of 9.85 kJ (7.26 kip-ft) are shown in Fig. 12a. All three piles were reasonably efficient to drive at the estimated geotechnical capacity. Timber is more efficient to drive at higher capacities. The fiberglass pile is stiffer than the reinforced polymer piling. However, the polymeric pile is much heavier than the empty fiberglass pile. Both factors evened out, and the driveablity of both piles was similar.

High Capacity Long Piles (170 tons)

The driveablity of steel core piling, fiberglass piling (driven empty and full of concrete) was compared to the driveablity of steel piling. The properties of all piles are shown in Table 3. A 27 m (90 ft) long pile having a nominal ultimate geotechnical capacity of 1670 kN (170 ton, 340 kips) was selected. Capacity was calculated according to NAVFAC DM 7 *(25)* as 880 kN (198 kips) in end bearing and 790 kN (142 kips) in skin friction. The calculated capacity is shown ± 10% on Fig. 12b as the estimated geotechnical capacity.

The bearing curves of piles analyzed using single acting VULCAN 10 hammer having a rated energy of 44 kJ (32.5 kip-ft) are shown in Fig. 12b. All four piles were reasonably efficient to drive at the estimated geotechnical capacity. The steel pipe, steel core, and fiberglass pipe piling drove similarly. Concrete filled fiberglass, which is the heaviest and stiffest, was the easiest to drive. Tensile stresses on the order of 14 MPa (2 Ksi) were calculated in the concrete filled fiberglass piling during easy driving. Similar values were also measured by Chernauskas and Paikowsky *(27)*. The tensile stresses in fiberglass piling was close to the ultimate strength, which is a cause for concern due to the lack of data on the performance of fiberglass under impact driving.

Effect of Piling Properties On Driveability

Wave equation analysis is sensitive to the unit weights of the materials involved. Typically, weight has little influence on the driveablity of conventional piles, because it is well defined. This is also true for concrete filled fiberglass pipe piles. However, weight and modulus play an important role for reinforced plastic piling and steel core piling. Generally, increase of specific weight reduces the required number of blows *(13, 24)*. Sections with a high composite modulus are also easier to drive.

An important issue related to driving polymeric materials is their anisotropy and non-homogeneity, which may result in localized areas of lower strength, particularly when recycled plastics are used. The drive-ability of conventional piling is mostly influenced by the soil parameters, while the drive-ability of softer polymeric sections depends mostly on the specific weight and elastic modulus of the pile material. Modulus and Specific weight can easily vary by ± 30% of their specified values, thus highlighting the importance of quality control during manufacturing. *(13, 24)*.

Composite action between the matrix and reinforcing elements plays an important role in reducing the driving stresses in steel pile core piling and concrete filled fiberglass pipe piling. Bond strength is critical to the development of composite action in all FRP composite piling. Delamination of some composite pile types has been reported in the past. However, manufactures claim that this problem has been solved.

ENVIRONMENTAL IMPACT

Composite piling offers a number of environmental advantages over conventional creosote treated timber piling, as follows:

- Treatment of timber using Creosote and CCA may pose a threat to marine life, particularly when a large number of piles is involved. Workers who handle creosote and CCA treated timber are also exposed to hazardous materials during manufacturing and installations. Additionally, treated timber present a growing environmental disposal problem since creosote is listed as toxin by The Environmental Protection Agency.

- 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 recycle plastics in FRP composite piling offers a solution to the mountains of solid plastic waste which are growing all over the United States and consuming valuable landfill space.

CONCLUSIONS

The existing composite piling materials offer a number of advantages and disadvantages. Advantages include durability and environmental dividends. Disadvantages include high cost, less efficient driveability, high compressibility, and lack of long term track record. Several barriers must be overcome for FRP composite piling to be accepted on a widespread basis. First, further definition of mechanical and physical properties is needed particularly under field conditions. Second, design and testing standards should be developed, and Third, several piles should be instrumented, installed, load tested, and monitored to verify theoretical and laboratory studies.

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LIST OF TABLES & FIGURES

Table 1 — Typical Mechanical Properties of Piling Materials

Parameter	Fiberglass Reinforcement	Recycled Plastic (HDPE)	Steel Reinforcement	Concrete
Tensile Properties, MPa (ksi)				
Ultimate Strength	485 (70)	7 (1)	310 (45)	1.4 (0.2)
Tensile Modulus	62,000 (9,000)	414 (60)	200,000 (29,000)	
Compressive Properties, MPa (ksi)				
Ultimate Strength	275 (40)	6.2 (0.9)	310 (45)	27.6 (4)
Compressive Modulus	51,000 (7,500)	310 (45)	200,000 (29,000)	25,000 (3,600)
Flexural Strength, MPa (ksi)	485 (70)	5.2 (0.75)	310 (45)	
Unit Weight kN/m^3 (pcf)	7.9 (50)	7 (45)	77 (490)	24 (150)

Table 2 — Assigned Properties of Low Capacity Piles (21 tons, 18m long)

Pile Type	Nominal Diameter	Piling OD	Pipe OD	Pipe ID	Area	Composite Modulus of Elasticity	Specific Weight	Pile Damping
	cm (in)	cm (in)	cm (in)	cm (in)	cm^2 (in^2)	MPa (ksi)	kN/m^3 (pcf)	
Reinforced Plastic	33 (13)	33 (13)	N/A	N/A	856 (132.7)	3,170 (460)	7.54 (48)	9
Fiberglass Pipe	35 (14)		35.6 (14)	34.16 (13.45)	76.4 (11.85)	51,000 (7500)	7.9 (50)	3
Timber	30 (12)	31.5 (12.5)	N/A	N/A	792 (122.8)	13,800 (2000)	8.0 (51)	5

Table 3 — Assigned Properties of High Capacity Piles (27 m long, 170 tons)

Pile Type	Nominal Diameter	Piling OD	Pipe OD	Pipe ID	Area	Composite Modulus of Elasticity	Specific Weight	Pile Damping
	cm (in)	cm (in)	cm (in)	cm (in)	cm^2 (in^2)	MPa (ksi)	kN/m^3 (pcf)	
Steel Pipe Pile	25 (10)	27 (10.75)	27 (10.75)	24.5 (9.75)	103.8 (16.1)	200,000 (29,000)	77.3 (492)	1
Concrete Filled Fiberglass	35 (14)		35.6 (14)	34.16 (13.45)	993 (154)	27,000 (4,000)	22 (140)	2–3
Steel Pipe Core Piling	40 (16)	39 (15.5)	27 (10.75)	24.5 (9.75)	735.5 (114)	25,500 (3700)	17.5 (112)	5
Fiberglass Pipe	35 (14)		35.6 (14)	34.16 (13.45)	76.4 (11.85)	51,000 (7500)	7.9 (50)	3

Fig. 1 Marine Borers (Limnoria) Attacking Untreated Timber Piles Which Support Many of New York's Pile Supported Highways and Harbor Piers.

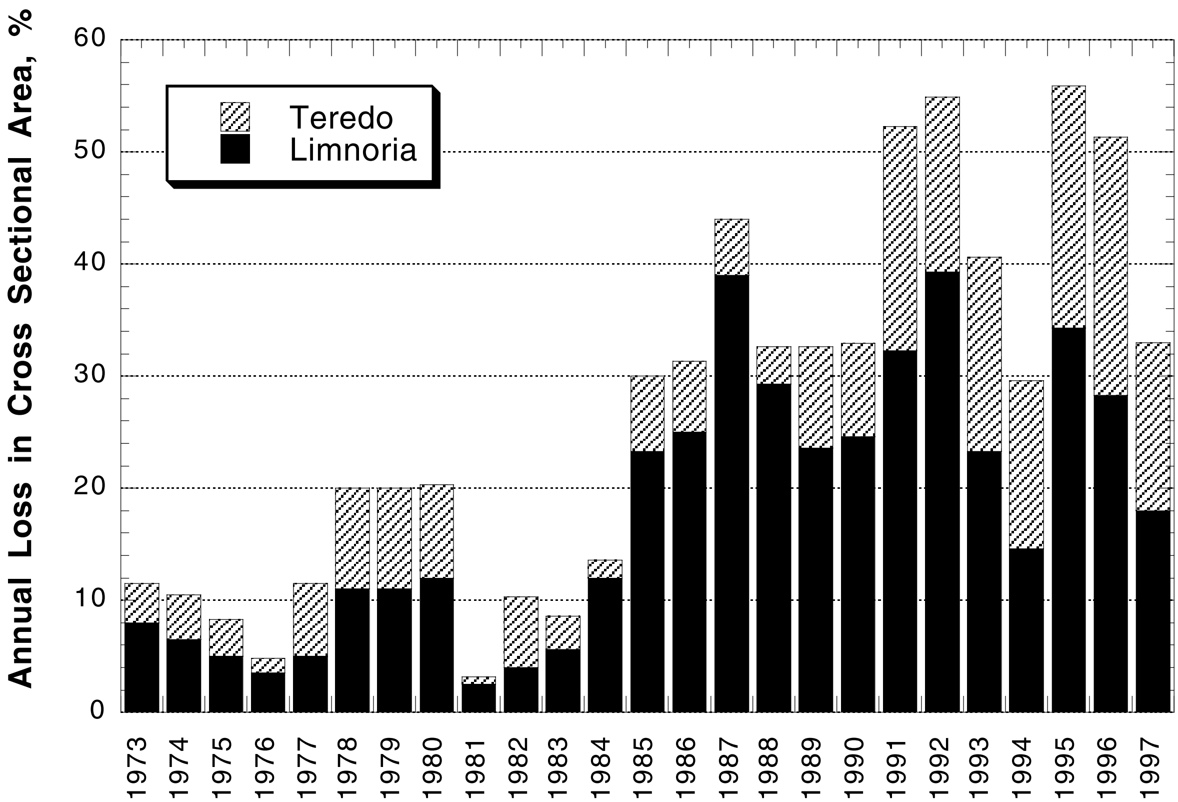


Fig. 2 Average Intensity of Marine Borers Attack on Untreated Timber in 32 Sites Monitored by The Port Authority of New York & New Jersey (After Bognacki & Gill, 1997)

Fig. 3 Numerous Ship-worms (Teredo and Bankia) Tunneling in A Timber Pile Make The Wood's Interior as Holed as Swiss Cheese.

Fig. 4 Complete Corrosion of Steel H Piles Supporting A Harbor Pier. Note That Recently Installed Retrofit Channels are Already Corroding

Fig. 5 Deterioration of Reinforced Concrete Piling Supporting a Harbor Pier, Causing it to Lose 65% of its Cross Sectional Area.

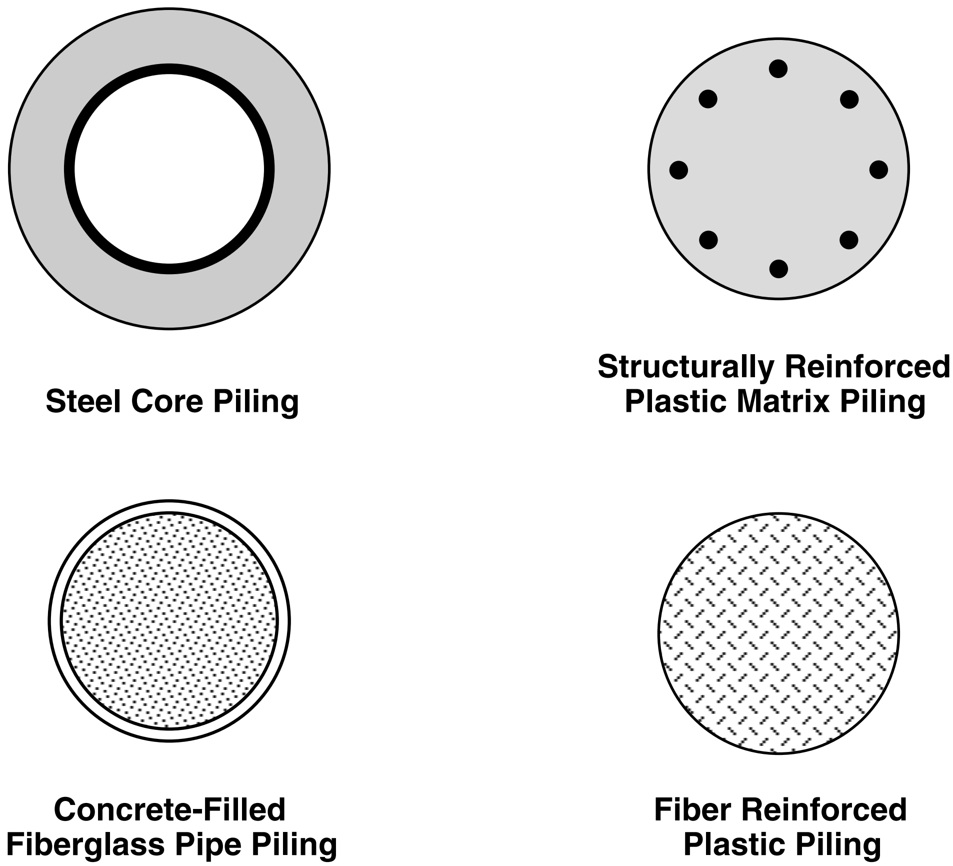


Fig. 6 Commercially Available FRP Composite Piling Products.

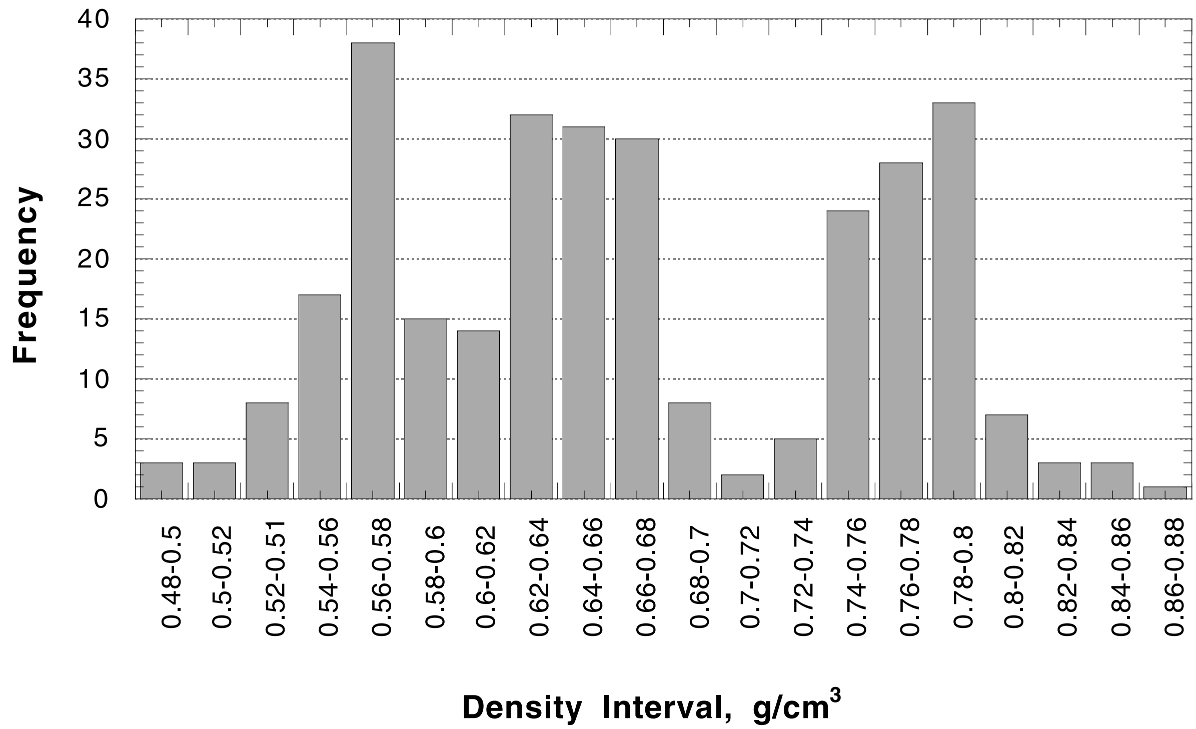


Fig. 7 Density Distribution of Tested Specimens

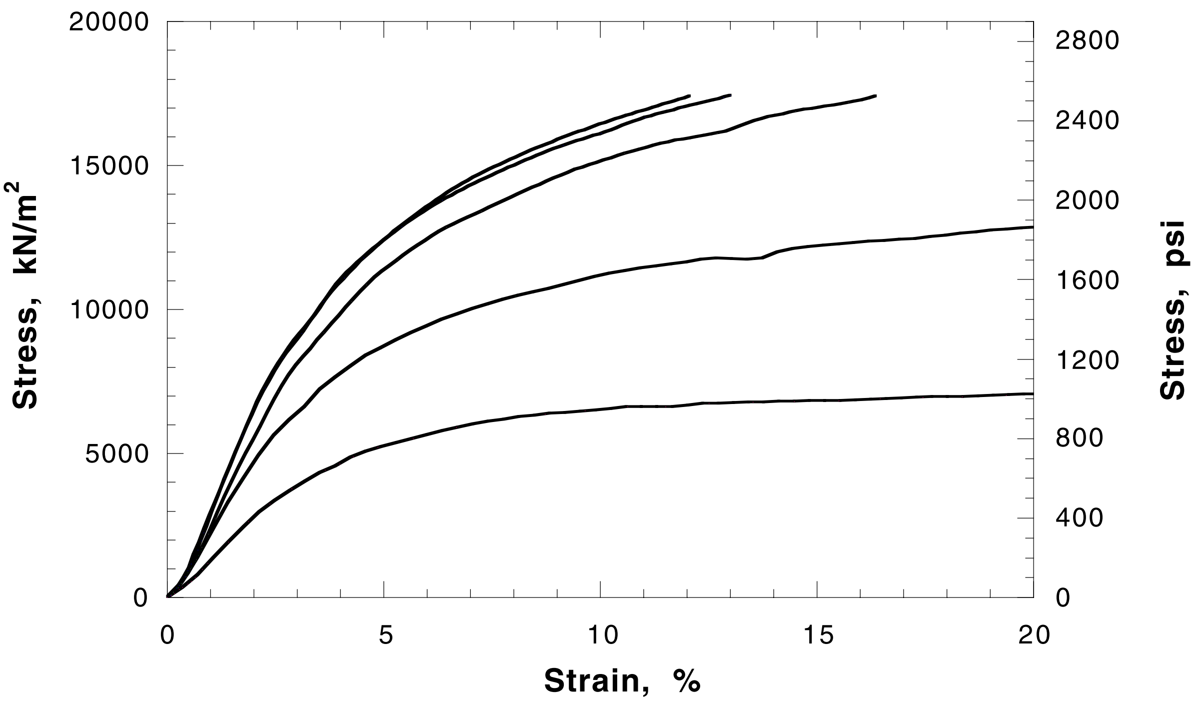


Fig. 8 Variation in Stress Strain Properties of Piling Made of Recycled Plastics. (All Tests Were Conducted Using Specimens Taken From The Same Pile)

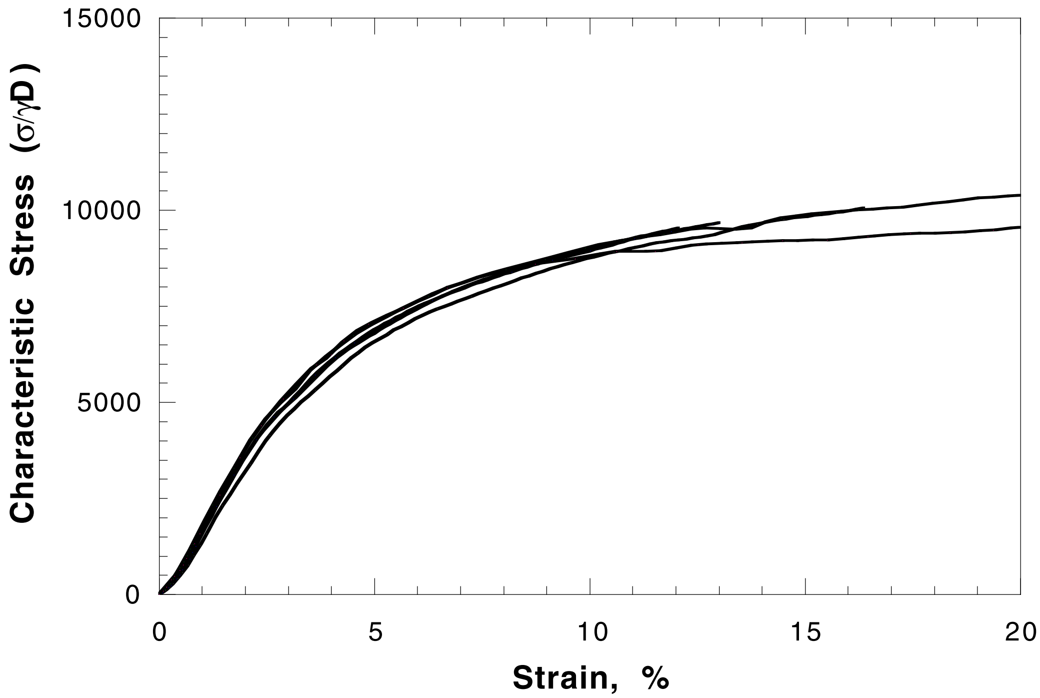


Fig. 9 Characteristic Strength vs. Strain Curves for the Conventional Stress Strain Curves Shown in Fig 8

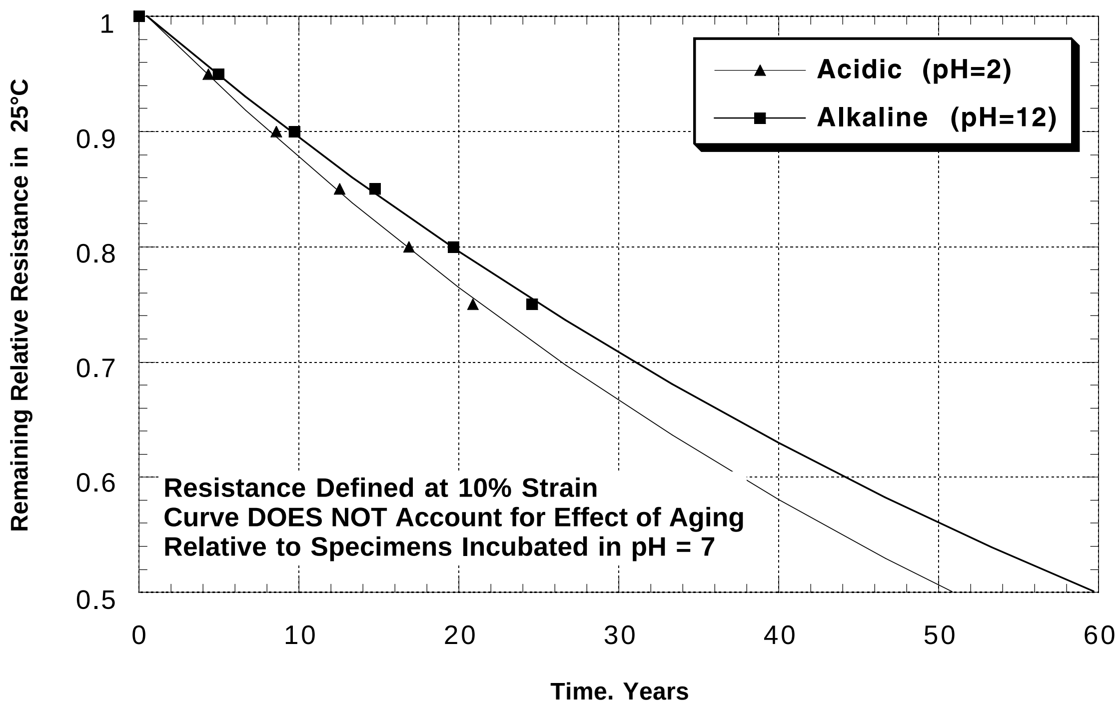


Fig. 10 Remaining Relative Resistance at 10% strain in Room Temperature

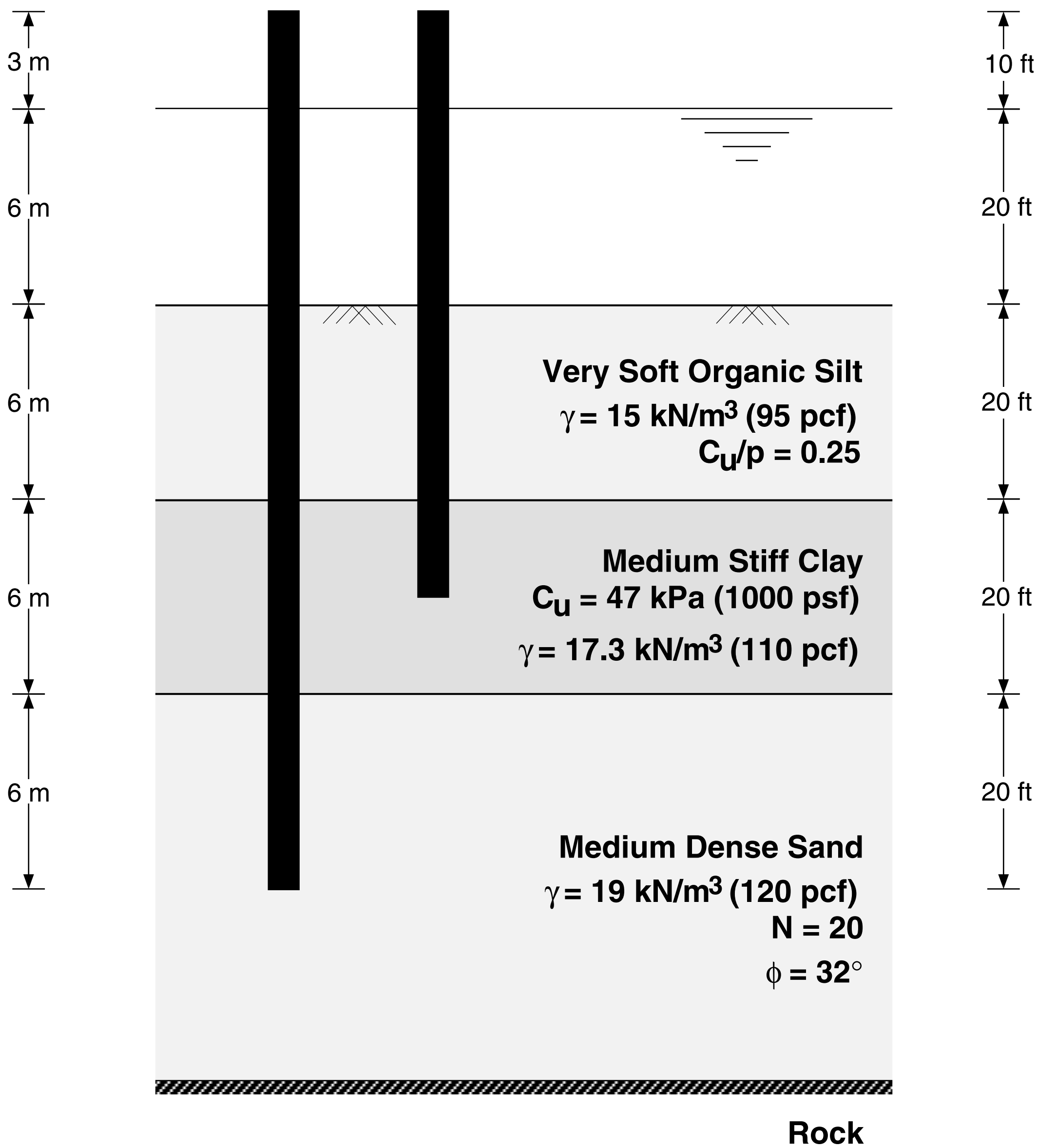
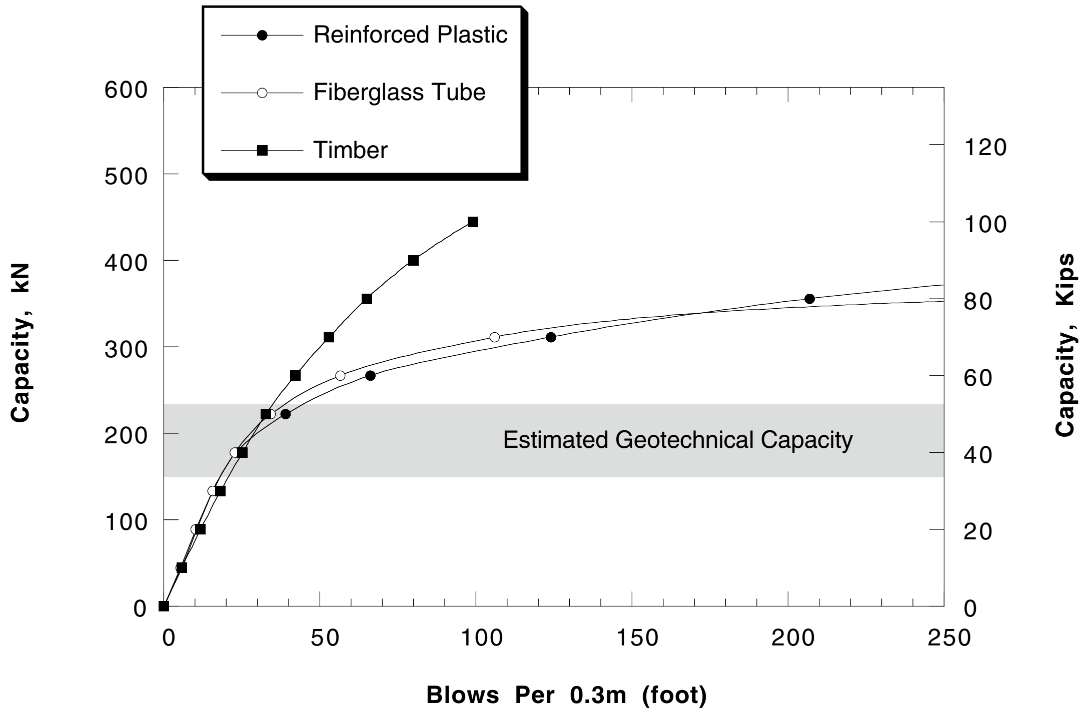


Fig. 11 Typical Manhattan Waterfront Soil Profile



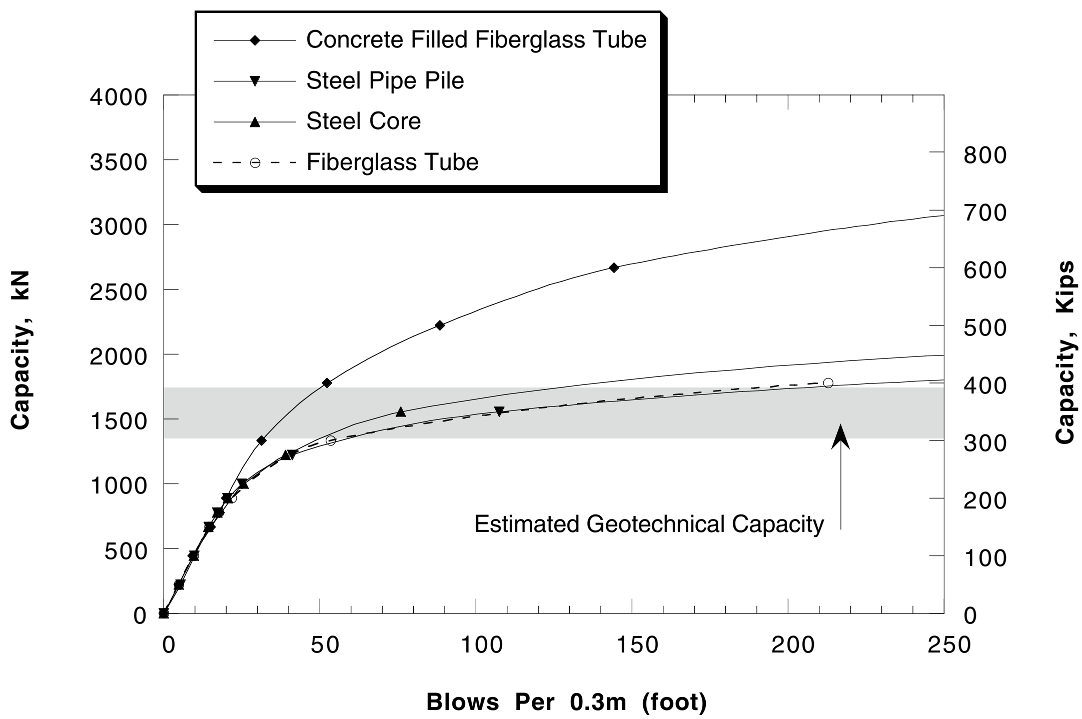


Fig. 12 Theoretical Bearing Graphs for (1) Low Capacity Short Piles (21 tons) and (2) High Capacity Long Piles (170 tons)