ENGINEERING PERFORMANCE OF FRP COMPOSITE PILING

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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

Sherif Hanna
Geotechnical Engineer
Parsons Brinckerhoff, FG, Inc
Princeton, NJ 08540
Phone: (609) 734-6963
Fax: (609) 734-6900
Email: Hannas@pbworld.com

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Magued G. Iskander, PhD, PE and Sherif Hanna

Magued Iskander, PhD, PE, Associate Professor, Polytechnic University, 6 Metrotech Center, Brooklyn, NY 11201
Sherif Hanna, Geotechnical Engineer, Parsons Brinckerhoff, FG, Inc, Princeton, NJ 08540

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. This paper presents a comprehensive summary of current research, testing, design, and practice of composite piling. The engineering performance of the available FRP composites is evaluated for use in piling applications.

INTRODUCTION

The first prototype recycled plastic pile was driven at The Port of Los Angeles in April 1987 (1). Since then, FRP composite piling has been used to a limited degree, or experimentally, in a number of ports and waterfront facilities (2). 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 (3).

The use of FRP composite piling has been propagated by the deterioration of conventional concrete, steel, and timber piling systems which cost nearly $1 billion annually for repair and replacement in the United States (4). 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 (5). At the same time, approximately 3.3 million tons of rigid plastic containers are landfilled annually in the United States (6). 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 (7).

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. Second, mechanical and physical properties should be defined and long-term performance should be verified under field conditions. Third, design methods for predicting driveablity and capacity should be developed *(8)*. Fourth, design and testing standards should be developed *(9)*, and fifth, piles should be instrumented, installed, load tested, and monitored at several well-documented sites.

This paper presents a comprehensive review of the state of the practice in FRP composite piling in summer 2002. Emphasis is given to the engineering performance, material properties, structural performance, durability, and driveability of available products.

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 *(10)*, 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. 1). Limnoria nibble at the outside edges of the timber piles causing timber piling to lose up to 1 inch in diameter yearly. 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. 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 slowed by coatings containing heavy metals, but these treatments are both harmful to the environment and not entirely effective.

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. 1). In marine environments, in addition to salts, the variation of temperature, freezing and thawing, further degrades the concrete.

AVAILABLE FRP COMPOSITE PILING PRODUCTS

In summer 2002, 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. 3). 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.) (12). 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. 3). 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.) (12, 13). 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 (14, 15). 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. A foaming agent is used to make the product lighter. Additives are also used to improve mechanical properties, durability, and ultraviolet (UV) protection. US Plastics and American Echo Board manufacture this product. The manufacturers produce a variety of structural members that conform to lumber industry standards. Piling is available in 25–40 cm (10–16 in.) diameter with a standard length of 6–7.5 m (18–24 ft.), but longer lengths could be custom made. In the last decade, plastic lumber has established a good track record in residential construction. However, use of the product in piling has been limited to demonstration and experimental projects.

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).

DURABILITY OF FRP COMPOSITE PILING

Virtually no information related to the durability of plastics in water front environments 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. 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. (16)* 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 *(17)*.

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 *(18, 19)* 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. 4). 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.

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.

- 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.

MECHANICAL PROPERTIES OF FRP PILING

Nominal properties of FRP composites are shown in Table 1, along with those of conventional materials. The physical and engineering properties of most polymeric piling typically exhibit a high coefficient of variation, particularly when recycled plastics are used (20). Nevertheless, this scatter can be attributed to the spatial distribution of strength and density within the specimens. The strength and density of foamed polymeric piling increased exponentially with distance from the center of the pile (Fig. 5 and 6). Strength was also found linearly proportional to density and inversely proportional to the degree of product foaming (Fig. 7).

When the stress vs. strain data of the coupon specimens shown in Fig. 8 were first plotted, a large scatter was observed even though the specimens came from the same pile. Dimensional analysis of the test results was used to reduce data scatter, and obtain a singular stress strain curve (21). The dimensionless term $\pi=\sigma/\gamma R$ was found representative of the stress strain curves for all specimen except those located immediately near the center of the pile (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.

BUCKLING BEHAVIOR OF FRP PILING

Buckling is typically ignored for conventional piling made of steel, concrete and timber. Because of their low modulus, FRP piling may buckle under extreme loading conditions or during driving. FRP has anisotropic material properties and high elastic to shear modulus ratio, which may result in large shear deformations. Han and Frost (22) evaluated the buckling of vertically loaded fiber reinforced polymer piling including the effects of shear deformations. They concluded that "*buckling of FRP piling may occur only when the surrounding soils are very soft or when a large portion of the pile extends above the ground*."

INTERFACE FRICTION OF FRP PILING

FRP has a lower surface hardness and a higher surface roughness than conventional piling materials. Experimental studies have been performed to characterize the interface behavior of FRP and soils. These studies yielded the following results

- Frost and Han (23) performed tests using an FRP made of a polyester matrix and glass fiber reinforcement and a sub-angular to angular sand (Valdosta Blasting Sand, D_{50} = 1mm). These tests concluded that the peak interface friction angle of the FRP/sand interface δ_{FRP} is larger than that of the steel/sand interface δ_{STEEL} by approximately 10% under a wide range of relative densities and normal stresses.

- Pando et al (24) performed tests using the fiberglass shell of a piling made by Lancaster composites, Inc. and Hardcore, Inc. Two sands were used. The first was fine to medium with a sub-angular to rounded grains (D_{50} = 0.50 mm). The second was a sub-angular to angular fine-grained sand (D_{50} = 0.18 mm). These tests concluded that the peak interface friction angle of the FRP/sand interface δ_{FRP} is 60-90 % of the concrete/sand interface δ_{CONCRETE}.

Considering that typically δ_{CONCRETE} greater or equal to δ_{STEEL}, it is suggested that, $\delta_{\text{FRP (FIBERGLASS)}} = \delta_{\text{STEEL}}$ can be used in the design of Fiberglass FRP piling. The interface friction of geosynthetics made of HDPE is typically in the range of 8-15°. Therefore, the interface friction angle of piling made of HDPE $\delta_{\text{FRP (HDPE)}}$ may be significantly lower than that of steel.

END BEARING OF FRP COMPOSITE PILING

Virtually no research has been performed on the bearing capacity of composite piling. Nevertheless, it is believed that the bearing capacity of composite piling is similar to that of conventional materials since bearing capacity is controlled by the properties of the soil, not the pile.

DESIGN CONSIDERATIONS FOR AXIAL LOADING OF FRP PILING

The design of piling made of conventional material is rarely concerned with the structural capacity of steel, concrete, or timber. These materials have well defined properties that exhibit little or no creep under service loads. Concrete, steel and timber are also much stronger than sand and clay. Therefore, soil properties dominate design considerations of piles. As a result, conventional design practice is mostly involved with determining a suitable factor of safety against geotechnical failure. Polymeric materials exhibit a non-linear elastoplastic behavior, which may influence the structural design of composite piling in a number of ways, as follows:

- It is expected that polymers respond differently according to the type, duration, and rate loading. Therefore, FRP piling systems are expected to resist rapid and short-term loads, such as driving loads, with less deformation than long term loads such as dead loads. Different moduli of elasticity are need for analysis of different loading conditions.

- The ultimate capacity of FRP materials is very high. Nevertheless, under long term loading, the allowable creep stress which is typically much smaller than the ultimate capacity of FRP may control the allowable structural load capacity of the pile. The viscoelatic creep of polymeric material may also influence soil structure interaction and the load transfer mechanism.

- FRP composite materials reach their ultimate capacities at different strains. For example, the maximum stress for HDPE and fiberglass (e-glass) is reached at 15% and 3%, respectively (21, 25). Therefore strain computability considerations make, the ultimate load capacity of composite members be dominated by the response of the stiffer material, particularly at small strains. The presence of the weaker material is however essential to prevent buckling of the entire cross section.

Additional research is needed to quantify these effects.

DRIVEABILITY OF FRP COMPOSITE PILING

The driveability of conventional piling is mostly influenced by the soil parameters, because conventional piling materials are much stiffer than the soils. Parametric studies conducted by the authors (25, 27) prove that that the driveability of softer polymeric sections depends mostly on the specific weight and elastic modulus of the pile material. Wave equation analysis (WEAP) of composite piling involves a number of variations from conventional analyses, as follows:

Input Parameters

The driveability of traditional piling can be predicted using wave equation analysis of piles (WEAP). The input parameters used in WEAP are obtained by back analyses of actual case histories. The properties of FRP piling differ from those of conventional piling, so conventional WEAP input parameters may not work as well for FRP composite piling. Iskander and Stachula (25) used available driving records to WEAP-input WEAP input parameters for composite piling. A secant modulus equal to two thirds of the initial tangent modulus is recommended to account for the non-linearity of polymeric materials. Also, a damping ratio of nine and was found to better predict field 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 (Fig. 10). Generally, increase of specific weight reduces the required number of blows. Sections with a high composite modulus are also easier to drive.

Residual Stress Analyses (RSA)

Polymeric materials exhibit a non-linear elastoplastic behavior similar to that of soils. In addition, polymeric materials have much lower stiffnesses than traditional piling materials (Table 1). These factors may result in the formation of high residual stresses in polymeric friction piles (27). The potential importance of RSA is illustrated by WEAP analyses in Fig. 11, where two 18.3-m (60-ft) long steel pipe and reinforced plastic piles, having similar capacities, are analyzed using WEA in uniform clay. Note that in order to achieve the same geotechnical capacity the polymeric pile required a larger hammer than the steel pipe pile. The hammer used in analysis of the polymeric pile was a Vulcan 012 having a rated energy of 53 kJ (39 kip-ft) and an enthru at the end of driving of 28.5 kJ (21 kip-ft). The hammer used in analysis of the steel pile was a Vulcan 01 having a rated energy of 20 kJ (15 kip-ft) and an enthru at the end of driving of 11 kJ (8 kip-ft). Failure to include residual stress analysis could result in the need to use an even larger hammer to drive the polymeric pile, and possibly over-stressing the pile during an actual installation.

Pile Properties

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. Modulus and Specific weight can easily vary by ± 30% of their specified values, thus highlighting the importance of quality control during manufacturing.

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 (25, 27). 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.

VIABILITY OF FRP COMPOSITE PILING FOR BEARING APPLICATIONS

All the available research suggest that FRP composite piling can be used for bearing of small axial loads, as long as appropriate material loading levels are not exceeded. This was recently confirmed in an ongoing load test program whose results will be reported soon.

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 a long-term record of accomplishment. 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, piles should be instrumented, installed, load tested, and monitored in several well documented sites to verify theoretical and laboratory studies.

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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)

Fig. 1 — Photographs of deteriorated piling in the New York Harbor. Clockwise (I) Toredo worms tunnel through timber piles. (ii) Limnoria worms attacking timber piles. (iii) Concrete pile deteriorated to 25% of its original cross section; and (iv) 100% corrosion of steel H-piles. Note retrofit channels are already corroding.

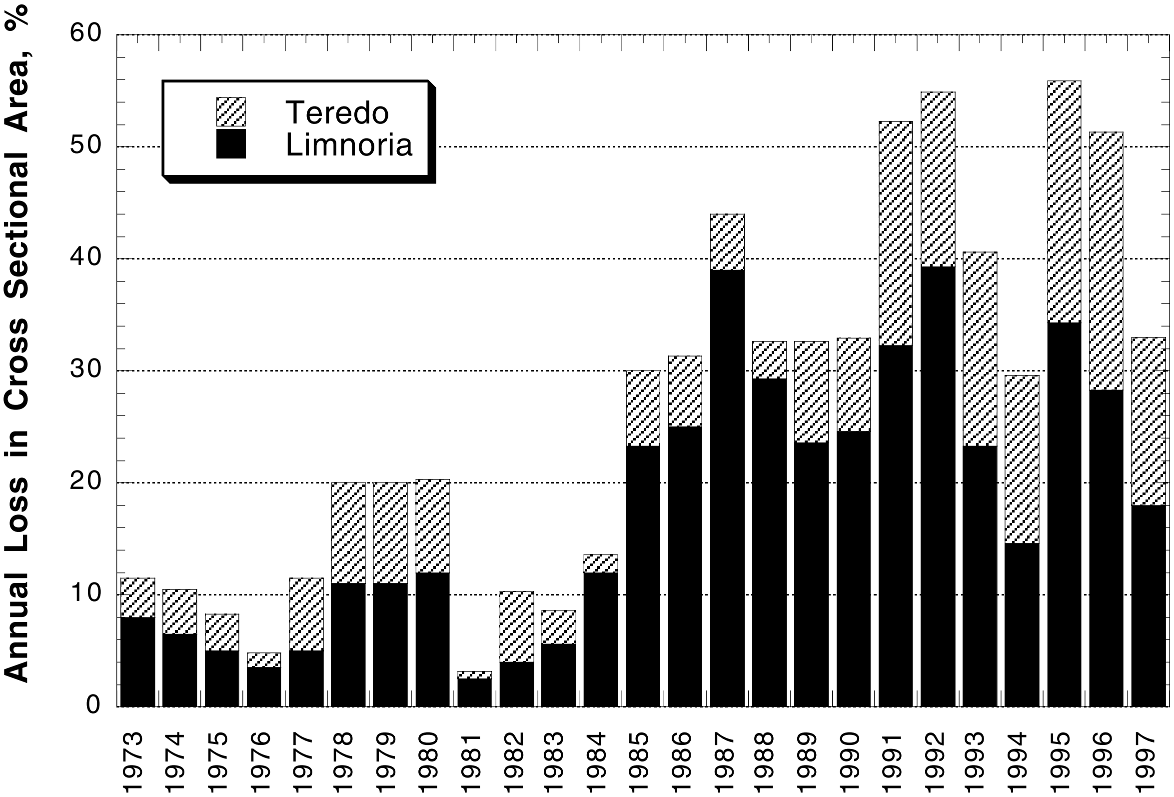
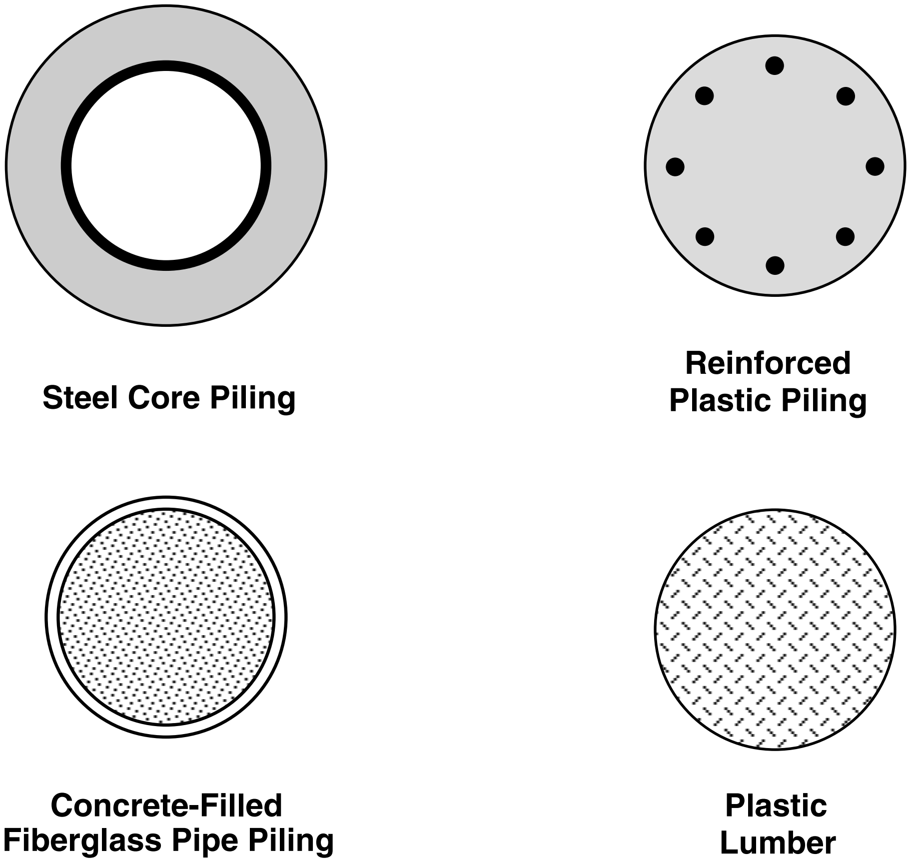


Fig. 2 — Average Intensity of Marine Borers Attack on Untreated Timber in 32 Sites Monitored by The Port Authority of New York & New Jersey (After Bognacki & Gill (10))



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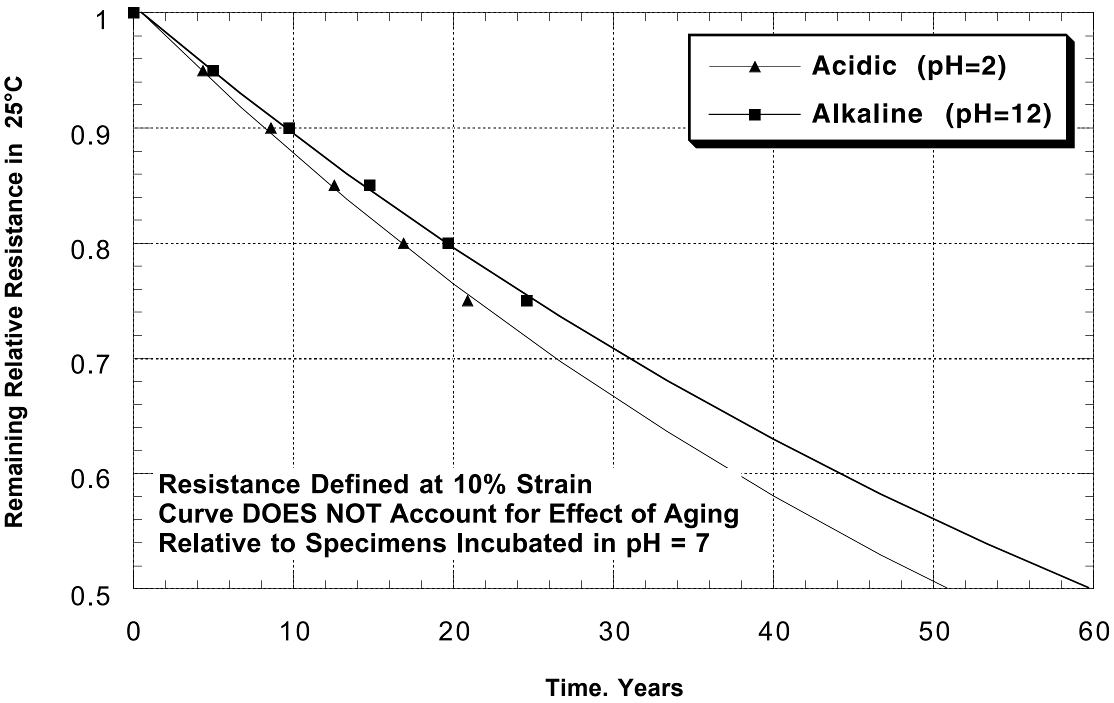

Fig. 4 — Remaining Relative Resistance at 10% strain in Room Temperature

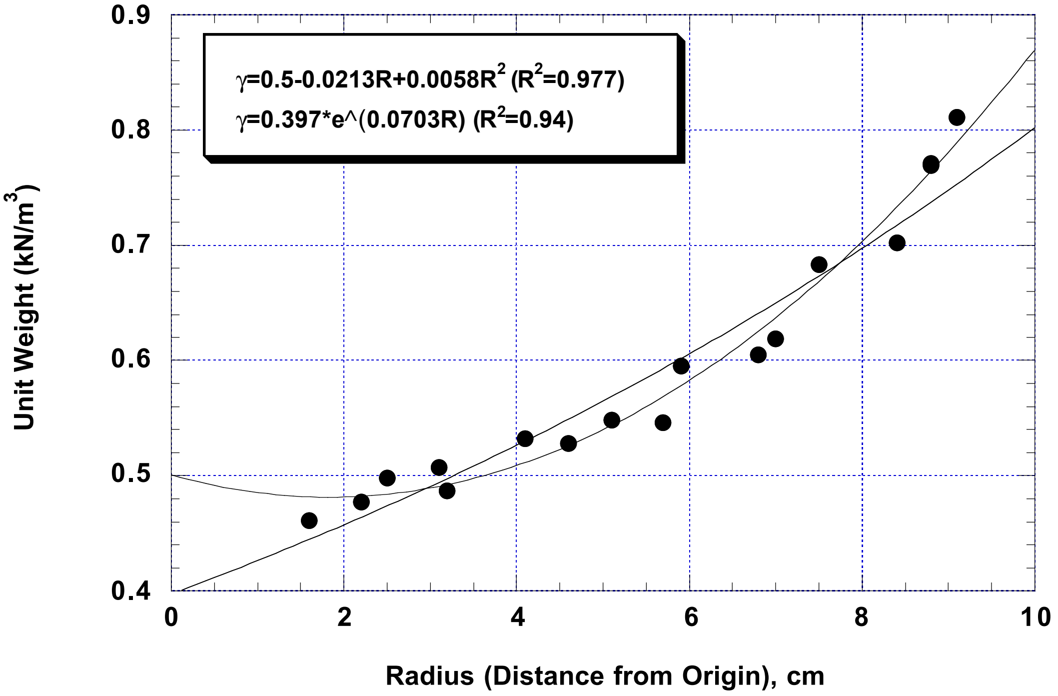

Fig. 5 – Density Distribution of Foamed Polymeric Piling

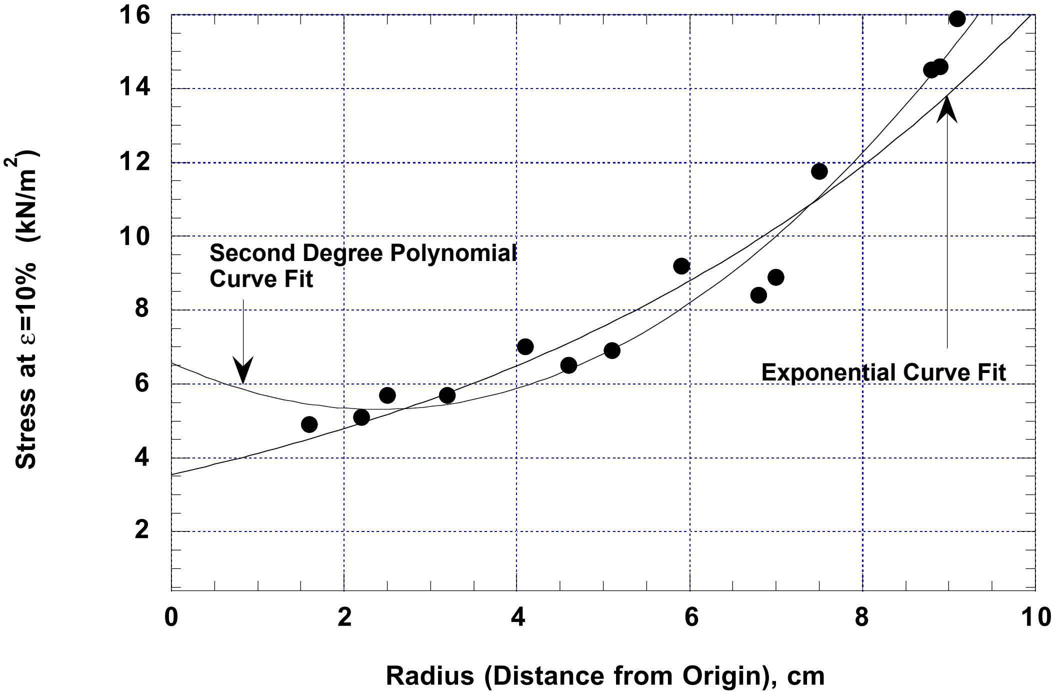

Fig. 6 — Typical Strength Distribution Within the Cross Section (ε = 10%).

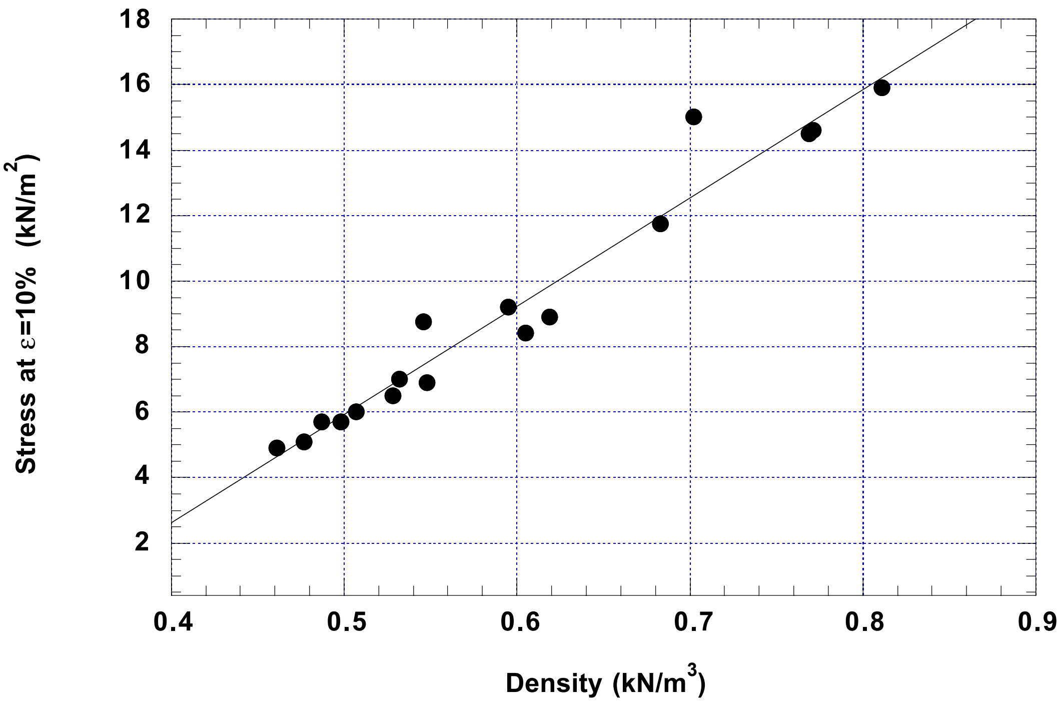

Fig. 7 — Linear Relationship Between Density and Strength Measured at 10% Strain For Foamed Polymeric Piling Specimens.

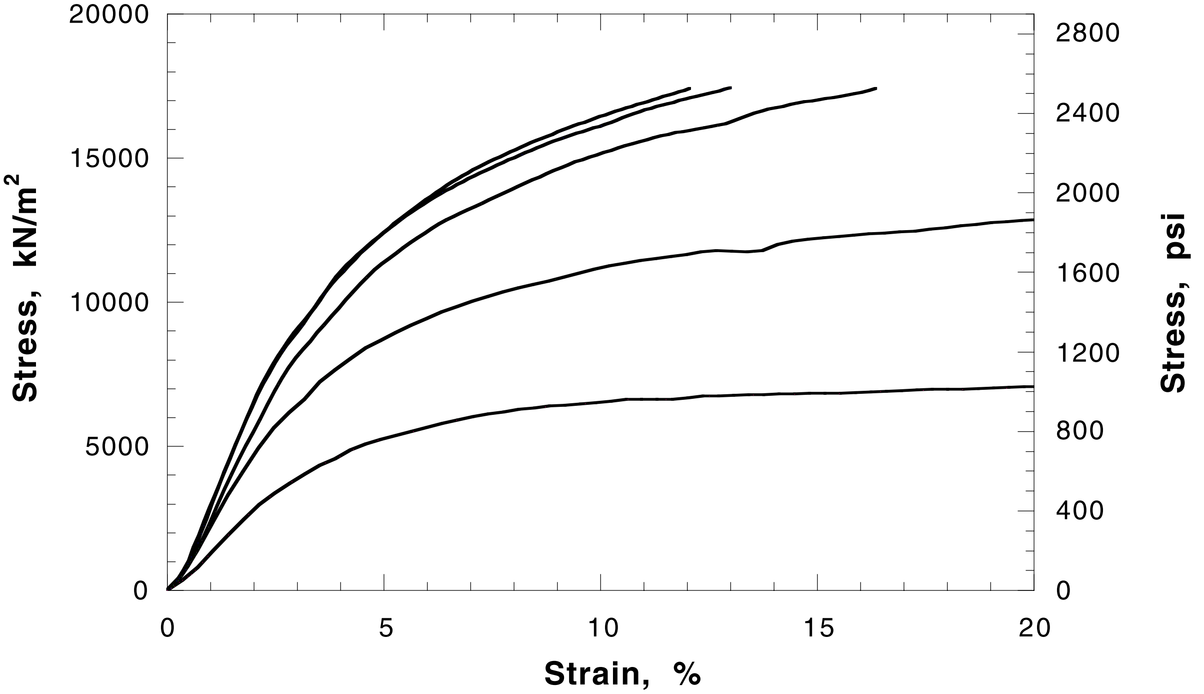

Fig. 8 – Variation in Stress Strain Properties of Piling Made of Recycled Plastics.

(All Tests Were Conducted Using Specimens Taken From The Same Pile)

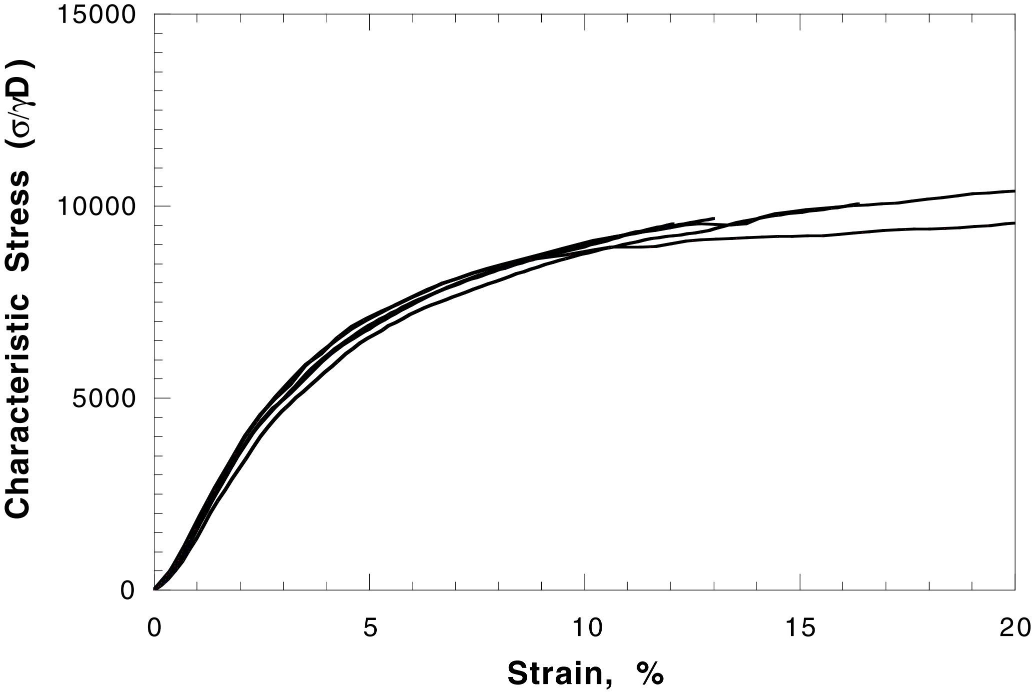

Fig. 9 — Characteristic Strength vs. Strain Curves for the Conventional Stress Strain Curves Shown in Fig 8

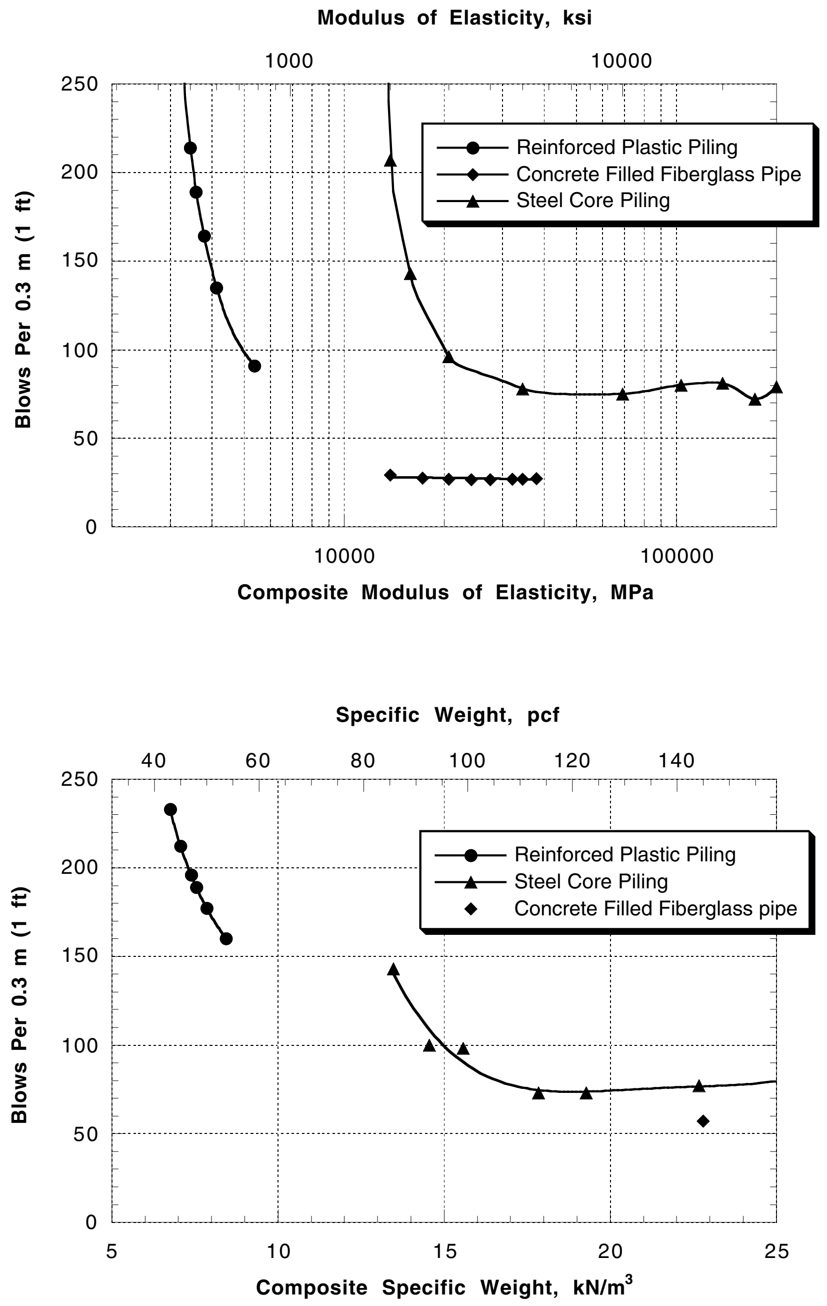

Fig.10 — Effect of the Elastic Modulus and Specific Weight on the Driveability of FRP Composite Piling

(Fixed Capacity For Each of The Three Piles in WEAP Analysis)

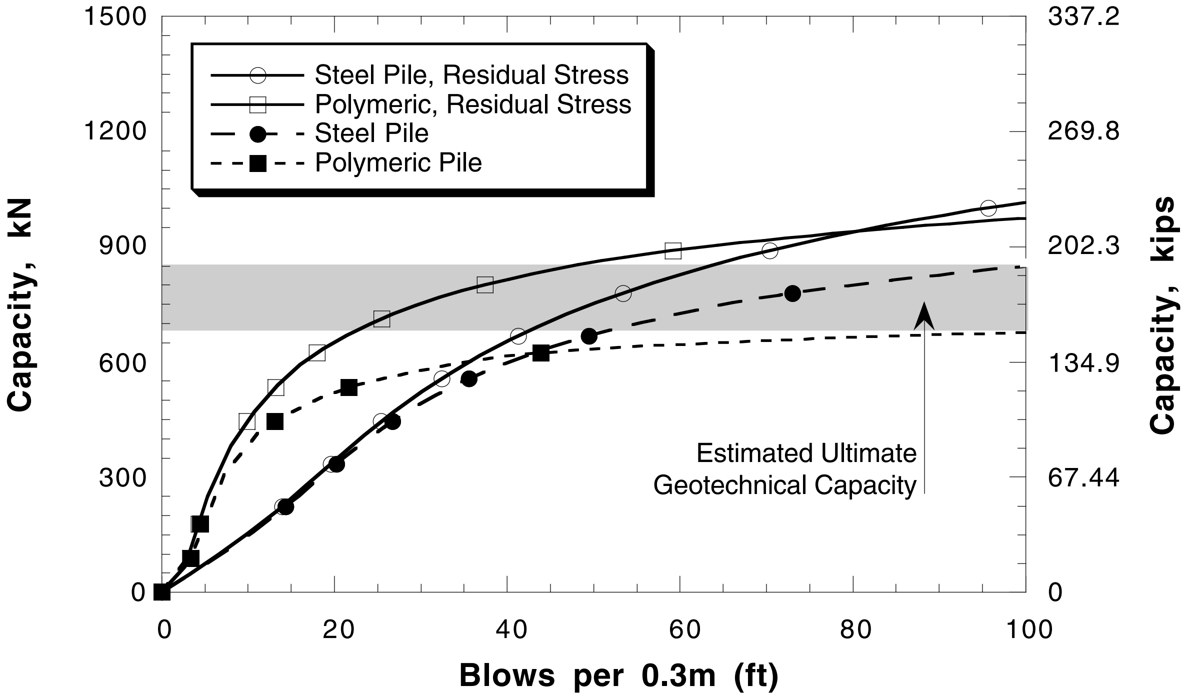

Fig. 11 — Effect of Residual Stress Analysis on Driveability of friction Piles (from WEAP)