FRP Composite Piling Practice
Practica de Pilotes Compuestos de Polímero de Fibras Reforzadas

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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 review of the current experience in research, testing, design, and practice of composite piling.

Resumen

El deterioro de concreto, acero y madera es un serio obstáculo para la construcción en la marina y en ambientes donde se presenta la corrosión. Materiales compuestos como el polímero de fibra reforzada pueden ofrecer buenas ventajas debido a su función en la construcción en este tipo de ambiente. En la última década, pilotes hechos de materiales compuestos se han utilizado experimetalmente por toda Norte América. Sin embargo, estos materiales compuestos enfrentan varios obstáculos, ya que no poseen un largo historial de su uso en las estructuras de ingeniería civil. Este reporte, ofrece una detallada y comprensiva explicación de las recientes experiencias obtenidas gracias a los estudios, experimentos, diseños y practica en general de pilotes compuestos.

1 INTRODUCTION

The use of FRP composite piling has been propagated by the deterioration of conventional piling systems (Fig. 1) which cost nearly $1 billion annually for repair and replacement in the United States (Lampo et al 1998). The Federal 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 that support many of the nation's harbor piers (Fig. 2, 3). At the same time, approximately 3.3 million tons of rigid plastic containers are landfilled annually in the United States (Lampo 1995). 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 (Tetra Tech 1999).

Figure 1. Complete Corrosion of Steel H Pile (top) & Loss of 65% of Cross Section of Concrete Pile (bottom)

Figure 2. Limnoria Attacks on the Exterior of Timber Piling (top). Ship Worms (Teredo and Bankia) Tunneling Through the Interior of a Timber pile (bottom)
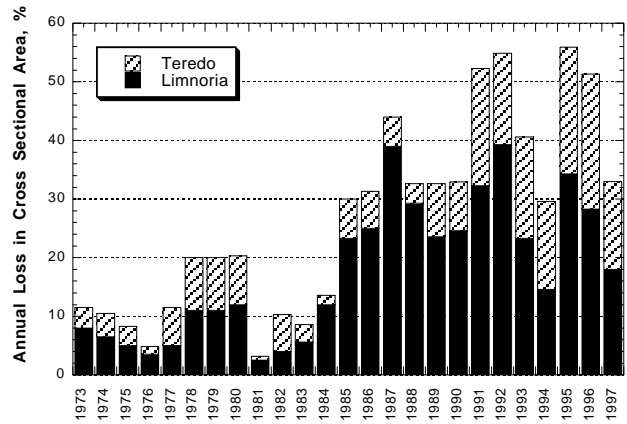

Figure 3. Average Intensity of Marine Borers Attack on Untreated Timber in 32 Sites Monitored By The Port Authority Of New York & New Jersey (Bognacki & Gill 1997)
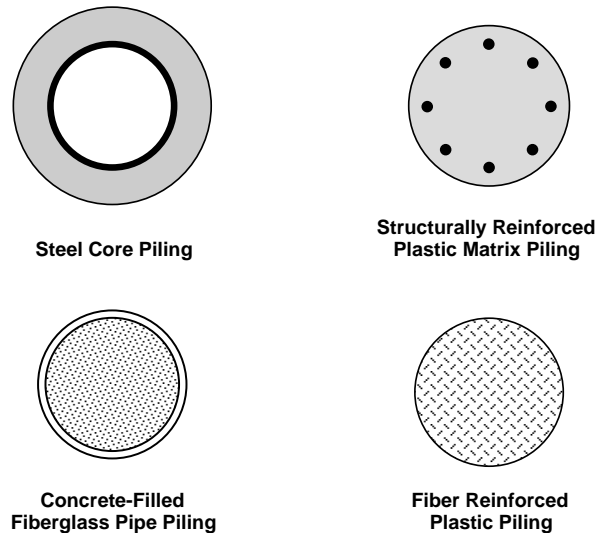
2 AVAILABLE PRODUCTS

The first prototype recycled plastic pile was driven at The Port of Los Angeles in April 1987. Since then, FRP composite piling has been used to a limited degree, or experimentally, in a number of ports and waterfront facilities (Iskander & Hassan 1998). 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. These products typically cost 2-3 times the cost of conventional piling but are expected to be more economic when life cycle costs are factored.

2.1 Steel Core Piling

Steel core piling was the first plastic piling product on the American market. It consist of a recycled plastic shell encasing a steel pipe core (Fig. 4). 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.).

Steel Core Piling

Structurally Reinforced Plastic Matrix Piling

Concrete-Filled Fiberglass Pipe Piling

Fiber Reinforced Plastic Piling

Figure 4. Commercially Available FRP Piling

2.2 Reinforced Plastic Piling

These piles typically consist of an extruded recycled HDPE plastic matrix reinforced with fiberglass or steel rods (Fig. 4). 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 strength. 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.).
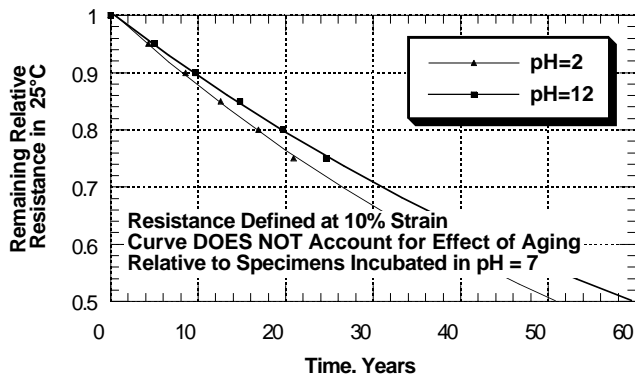
Figure 5. Remaining Relative Resistance at 10% strain in Room Temperature

2.3 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. Piles are typically filled with concrete and cured, prior to driving. 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.

2.4 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 UV protection. 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.

2.5 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 (6in) in diameter/width and come in lengths up to 6m (20 ft).

3 DURABILITY

Iskander & Hassan (2001) 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. 5). 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 (Iskander et al 2002). 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.

4 ENVIRONMENTAL IMPACT

Composite piling offers a number of environmental advantages over conventional creosote treated timber piling. 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 also 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. Finally, 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.

5 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
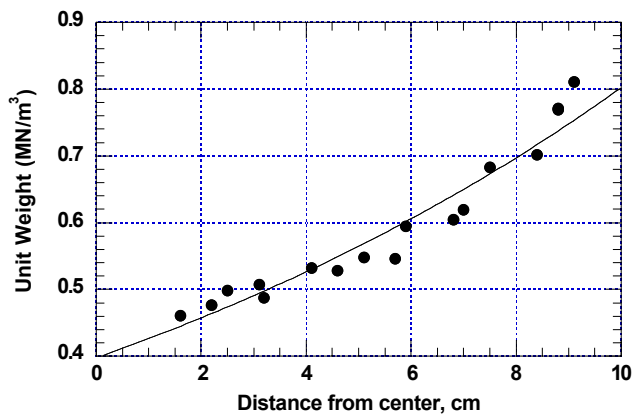
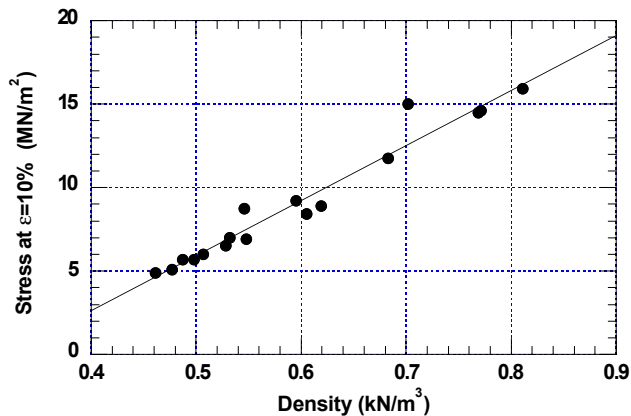Figure 5. Density Distribution of Foamed Polymeric Piling

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

Fig. 6 — Linear Relationship Between Density and Strength Measured at 10% Strain For Foamed Polymeric Piling Specimens.

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

Table 1 — Typical Mechanical Properties of FRP

Parameter	Fiberglass	HDPE
Tensile, MPa (ksi)		
Ultimate Strength	485 (70)	7 (1)
Tensile Modulus	62,000 (9,000)	414 (60)
Compressive, MPa (ksi)		
Ultimate Strength	275 (40)	6.2 (0.9)
Compressive Modulus	51,000 (7,500)	310 (45)
Flexural Strength, MPa (ksi)	485 (70)	5.2 (0.75)
Unit Weight kN/m³ (pcf)	7.9 (50)	7 (45)

typically exhibit a high coefficient of variation, particularly when recycled plastics are used (Warren 1996). Nevertheless, this scatter can be attributed to the spatial distribution of strength and density within the specimens. The density of foamed polymeric piling increases exponentially with distance from the center of the pile (Fig. 5). Strength was also found linearly proportional to density (Fig. 6).
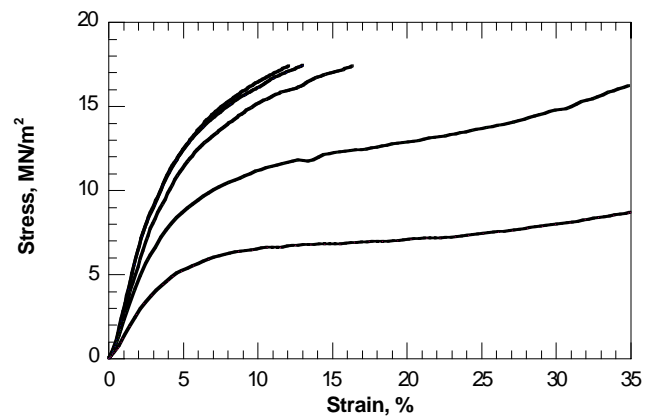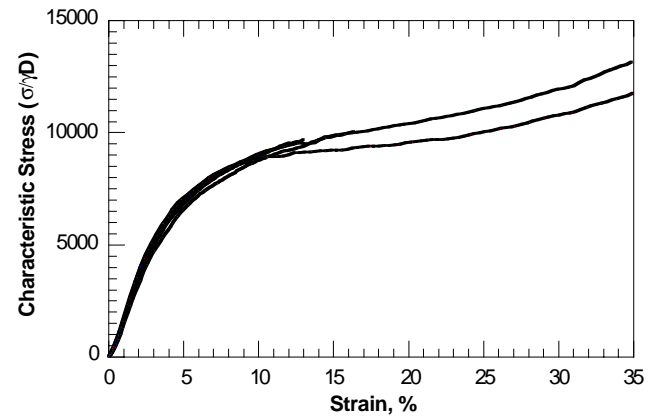
When the stress vs. strain data of the coupon specimens shown in Fig. 8 were first plotted, a large scatter was observed even though the specimens came from the same pile. Dimensional analysis of the test results was used to reduce data scatter, and obtain a singular stress strain curve (Iskander et al 2003). 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.

6 BUCKLING BEHAVIOR

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 (1999) 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."

7 INTERFACE FRICTION

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 (1999) 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 d 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 (2002) 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 d FRP is 60-90 % of the concrete/sand interface $\delta_{CONCRETE}$.

Considering that typically $\delta_{CONCRETE}$ is greater or equal to δ_{STEEL}, it is suggested that δ_{FRP} (FIBERGLASS) = δ_{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 $\delta_{FRP (HDPE)}$ may be significantly lower than that of steel.

8 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.

9 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.

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 (Iskander 2003, Hollaway 1990). Therefore strain compatibility 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.

10 DRIVEABILITY

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 Iskander et al (2001) 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:
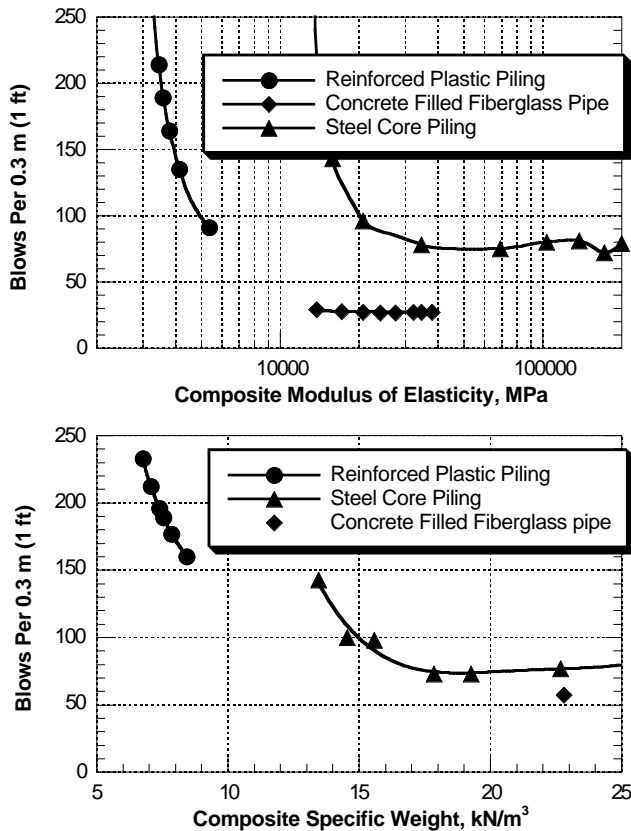

Fig.10 — Effect of the Elastic Modulus and Specific Weight on the Driveability of FRP Composite Piling (Fixed Capacity For Each of The Three Piles in WEAP Analysis)
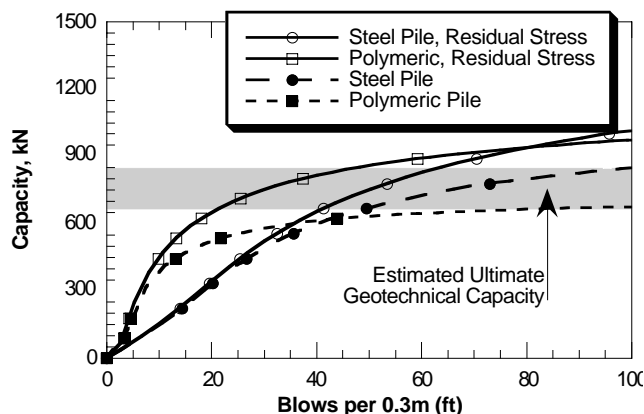

Fig. 11 — Effect of Residual Stress Analysis on Driveability of friction Piles (from WEAP)

10.1 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 (2002) 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.

10.2 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. 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.

10.3 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. 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.

11 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.

12 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.

13 ACKNOWLEDGMENTS

14 REFERENCES

Bognacki, C. and R. Gill (1997) 1995–1997 Marine Borer Report, Materials Engineering Division, Engineerig Department, Port Authority of NY & NJ

Frost, J. D. and Han, J. (1999) "Behavior of Interfaces Between Fiber Reinforced Polymers and Sands," ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 125, No.8, pp. 633–640

Han J. and D. Frost (1999) Buckling of Vertically Loaded Fiber-Reinforced Polymer Piles, Journal of Reinforced plastics and Composites, Vol. 18, No. 4, pp. 290–318

Hollaway L. (1990) Polymers and Polymer Composites in Construction, Thomas Telford, London

Iskander, M and Hassan, M. (1998) "State of The Practice Review FRP Composite Piling," ASCE Journal of Composites for Construction, August, Vol.2, No. 3, pp. 116–120

Iskander, M and Hassan, M. (2001) "Accelerated Degradation of Recycled Plastic Piling in Aggressive Soils," ASCE Journal of Composites for Construction, August, Vol.5, No. 3

Iskander, M and Stachula, A. (1999) "FRP Composite Polymer Piling An Alternative to Timber Piling For Water-Front Applications," Geotechnical News, vol. 17, No. 4, pp. 27-31

Iskander, M Hanna, S. and Stachula, A. (2001) "Driveability of FRP composite Piling," ASCE Journal of Geotechnical and Geoenvironmental Engineering, Feb, Vol.127, No. 2, pp. 169–176

Iskander, M Mohamed A. and Hassan, M. (2002) "Durability of Recycled FRP Piling in Aggressive Environments," in press, Transportation Research Record, Journal of Transportation Research Board and Proc. Transportation Research Board Meeting, Jan. 2002, CD, National Academy Press.

Iskander, M, A. Mohamed and S. Sadek (2003) "Compress Compressive Strength of Foamed Polymeric Piling" in press, Proc. TRB January 2003.

Lampo, R. (1995). "Recycled Plastics as an Engineered Material." Proc. XIII Struct. Congress, Restructuring America and Beyond, Sanayei, M., ed., Vol. 1, pp. 815-818, ASCE, Reston, VA

Lampo, R., Nosker, T., Barno, D., Busel, J., Maher, A., Dutta, P., and Odello, R. (1998). Development and Demonstration of FRP Composite Fender, Load-bearing, and Sheet Piling Systems, Report, US Army Corps of Engineers, Construction Engineering Research Laboratories, Champaign, IL 61826-9005.

Pando, M., G. Filtz, J. Dove, and E. Hope (2002) "Interface Shear Tests on FRP Composite Piles," Proceedings, Deep Foundations 2002, Orlando, GSP N0. 116, pp. 148–500

Tetra Tech (1999) Plastic Pier Piling Evaluation Report, Reprt Prepared for Navy Region Southwest, Navy Environmental Leadership Program, Tetra

Tech EM, Inc, 591 Camino De La Reina, #640, San Diego, CA 92108, Contract no. N62474-94-D-7609

Warren, G. (1996) Limited Flexural Tests of Plastic Composite Pile Configurations Special Publication SP-2005-SHR, Naval Facilities Engineering Service Center, Port Hueneme, CA 93043