

CHAPTER 11

SUMMARY AND CONCLUSIONS

11.1 INTRODUCTION

This study investigated the potential of using composite piles for load bearing applications, specifically bridge substructures. Composite piles refer to alternative pile foundations composed of fiber reinforced polymers (FRP's), recycled plastics, or hybrid materials that are placed in the ground to support axial and/or lateral loads. Traditionally, piles are made of steel, concrete, and timber. These pile materials have limited service life and high maintenance costs when used in harsh marine environments (Lampo et al. 1998). Degradation problems of conventional piles include chloride attack on concrete, steel corrosion, and marine borer attack on timber piles. It has been estimated that repair and replacement of piling systems costs the U.S. over \$1 billion annually (Lampo et al. 1997). High repair and replacement costs drive the need to investigate the feasibility of using FRP composite materials for pile foundations (Lampo et al. 1998; Iskander and Hassan 1998). FRP composite materials are considered an attractive alternative for marine and other harsh environments because they are resistant to the degradation mechanisms mentioned above.

Composite piles have been available in the North American market since the mid 1980's, but their use to date has been limited mainly to marine fender piles, load bearing piles for light structures, and experimental test piles (Iskander et al. 2001). Composite piles have not yet gained wide acceptance in the civil engineering industry, primarily due to the lack of a long track record of performance. However, FRP composite piles may exhibit a longer life cycle and improved durability in harsh marine environments, which presents the potential for substantially reduced costs.

In order to confidently establish the feasibility of using composite piles for load-bearing structures, information and performance data was gathered in critical areas of structural behavior and performance, long-term durability, and geotechnical behavior, including driveability and soil-pile load transfer interactions. The overall objective of this research project was to establish the feasibility of using composite piles in bridge substructures. Table 11.1 outlines the four detailed objectives of the project and indicates how each objective was met.

Table 11.1 Detailed project objectives

Objective	Evidence of objective completion
1. Evaluation of the long-term durability of concrete-filled FRP composite pipe piles.	An experimental study was designed and implemented to investigate the degradation of the mechanical properties of glass FRP composites used to fabricate composite piles. The study investigated the effects of moisture absorption and exposure to freeze-thaw cycles.
2. Performance of laboratory tests to evaluate the soil-pile interface behavior of concrete-filled FRP composite pipe piles and compare them with tests carried out on conventional prestressed concrete piles.	Interface shear tests were carried out on four FRP composite piles, one plastic pile, and two conventional piles.
3. Design and performance of a test pile program to evaluate the driveability and axial and lateral behavior and capacity of concrete-filled FRP composite pipe piles compared to conventional prestressed concrete piles.	Full-scale test pile programs were performed at two bridge sites in Virginia. Field data was gathered, analyzed, and disseminated to help contribute to the current state of knowledge of composite piles.
4. Design and performance of a production pile testing and monitoring program in a real bridge project to compare long-term performance, load-transfer, and durability of concrete-filled FRP composite pipe piles and conventional prestressed concrete piles.	A long-term monitoring program was designed and implemented at the Route 351 bridge. The program consisted on instrumenting two production piles of the bridge: a concrete-filled FRP pile and a conventional prestressed concrete pile. The long-term monitoring of the instrumented piles will provide useful information to compare the long-term performance of these two pile types. The long term monitoring will be carried out by the Virginia Department of Transportation.

The remainder of this chapter provides summaries of activities performed and conclusions drawn. The chapter concludes with a discussion of the practical implications of this research, and recommendations for future research.

11.2 SUMMARY OF ACTIVITIES AND CONCLUSIONS

This section summarizes the activities and conclusions for the following: the literature review, the interface laboratory study, the durability study of concrete-filled FRP tubular piles, the field tests at the Route 40 and Route 351 bridge projects, the analytical studies on axial and lateral behavior, the long term monitoring program, and the composite pile cost information.

11.2.1 Literature Review

A literature review was performed to: 1) identify suitable composite pile candidates to be used in high load-bearing projects such as bridge substructures, 2) identify the research needs, and 3) help design the work plan for this research project.

11.2.2 Interface Study

The following laboratory activities were performed for the interface study:

- Selection of sand specimens for interface testing.
- Soil characterization tests to determine grain size distribution, minimum/maximum density, and specific gravity testing.
- Direct shear tests on Density and Model sands to determine internal friction angles.
- Selection of pile surface specimens for interface testing.
- Surface topography characterization and surface hardness determination of seven pile surfaces. The seven pile surfaces included four FRP composites (commercially available from two FRP composite pile manufacturers), one recycled plastic pile, and two conventional pile materials (a prestressed concrete pile and a steel sheet pile).
- Design and construction of a modified top half shear box to permit testing of curved pile surfaces obtained from the FRP composite tubes.

- Interface shear tests for the seven piles and two sand types to determine the interface behavior and interface friction angles of these interfaces.

A series of interface shear tests were performed on fourteen types of soil-pile interfaces. Tests were carried out for two types of sands: Density sand ($D_{50} = 0.5$ mm, subrounded to rounded particle shape) and Model sand ($D_{50} = 0.18$ mm, subangular to angular particle shape). Seven pile surfaces were tested: Lancaster FRP composite (curved), Hardcore FRP composite (curved), Hardcore FRP composite plate (flat), Hardcore FRP composite plate with bonded sand treatment (flat), PPI recycled plastic coupon (flat), prestressed concrete pile coupon (flat), and a steel sheet pile coupon (flat).

The peak and residual interface friction angles for the 14 sand-to-pile interfaces tested are summarized in Tables 3.6 through 3.8.

From the results of the interface study, the following conclusions and observations were made:

- The interface friction angle values obtained for the Density sand tested against the Lancaster FRP composite pile were much lower than the values obtained for the other pile surfaces. The peak and residual interface friction angles obtained for the Lancaster FRP composite pile were 19.7° and 16.6° , respectively. In contrast, the interface friction angle values obtained for the Density sand tested against the other pile surface types ranged from 27.6° to 33° , and from 24.9° to 27.8° , for the peak and residual conditions, respectively.
- The Lancaster FRP composite pile was measured to have the largest average mean line spacing, S_m , and the second lowest maximum peak to valley height, R_t (as reported in Table 3.6). These values make this pile surface the smoothest of all seven surfaces tested.
- In general, the subangular to angular Model sand gives slightly higher interface friction angles than the subrounded to rounded Density sand. However, for the Lancaster FRP composite pile the interface friction angles obtained with the Model sand are much higher than the Density sand values.
- In general, the interface friction angles, both peak and residual, were found to increase with increasing relative asperity height, R_t/D_{50} .
- In general, the interface friction angles, both peak and residual, were found to increase with decreasing relative spacing, S_m/D_{50} , which is reasonable over the range of S_m/D_{50} tested.

- Linear regression analyses between the interface friction coefficients and the variables R_t/D_{50} , S_m/D_{50} , and HV, showed moderate fit strengths (where R_t and S_m are surface roughness parameters and HV is the Vickers hardness number). The regression analyses suggest other factors besides R_t/D_{50} , S_m/D_{50} , and HV also have important influences on the values of interface friction coefficient.
- The bonded sand surface treatment used for the Hardcore FRP plate was successful in increasing the interface friction angle values.

11.2.3 Durability Study

A laboratory testing program was completed to study the long-term performance of FRP composite pipe piles. This durability study addresses the FRP shells of the Lancaster and Hardcore composite piles, and included FRP shell characterization, determination of baseline mechanical properties, measurement of moisture absorption as a function of time and temperature, measurement of mechanical properties as a function of moisture absorption, and measurement of mechanical properties as a function of freeze-thaw cycles.

From the results of the durability study, the following conclusions and observations were made:

- The experimental program revealed strength and stiffness degradation due to moisture absorption at room temperature of up to 25% for the E-glass composites tested. These levels of degradation correspond for steady state moisture contents reached after about 2.5 years of submergence.
- Degradation of longitudinal mechanical properties for the 24-inch Lancaster pile was not as significant as for the Hardcore pile because of the different fiber lay-ups. The Lancaster pile was matrix dominated in the longitudinal direction since the fibers with closest alignment to the longitudinal axis were 35 degrees off alignment.
- For the composite piles with fiber dominated composite, the levels of degradation of mechanical properties were similar in hoop and axial direction.
- The impact of FRP degradation on the long term structural capacity of the piles was investigated using models by Fam (2000). This approach showed that, for a 12-inch diameter FRP pile, the axial structural capacity will decrease about 5% if the FRP tube hoop properties degrade 25% and 40% in stiffness and strength, respectively. The small impact that the FRP degradation has on the axial pile capacity is due to the fact that majority of the capacity contribution is coming

from the concrete infill. The impact on larger diameter piles is even smaller. A similar analysis was carried out for flexural capacity of a 12-inch pile. The results show that a 24% reduction in flexural capacity can be expected if the FRP tube longitudinal tensile properties degrade 25% and 40% in stiffness and strength, respectively.

- Exposure to freeze-thaw cycles was found to have little effect on the longitudinal tensile properties of the saturated FRP tubes. This is based on longitudinal tensile tests on samples exposed to 100, 300, and 500 freeze-thaw cycles.

11.2.4 Field Tests at the Route 40 Bridge

In 2000, the Virginia Department of Transportation (VDOT) replaced the old Route 40 Bridge (Structure No. 1006) over the Nottoway River. New precast composite piles, consisting of concrete-filled Glass-FRP tubes, were used to support one of the cast-in-place reinforced concrete cap beams that directly support the superstructure. Prior to construction, full-scale field tests were undertaken to investigate the feasibility of construction, handling, and drivability, as well as the structural performance of the new composite piles in comparison to conventional prestressed concrete piles.

Based on the testing, analysis, and construction experience at the Route 40 bridge, the following conclusions and observations were made:

- Both the composite and prestressed concrete piles performed similarly in the axial load tests. Full geotechnical capacity was mobilized in both cases without structural failure of the piles. The axial loads at geotechnical capacity were significantly higher than the design pile load.
- Initially, the composite test pile exhibited a lateral stiffness similar to that of the prestressed concrete test pile up to a load of about 40 to 50 kN. This load level was found to correspond to first cracking of the composite pile. Beyond this load, the composite pile exhibited a much lower stiffness than the prestressed concrete pile, but the composite pile did demonstrate continuing ability to sustain lateral load with additional relatively large deformations.
- The flexural strength of the 625 mm (24.6 in.) diameter composite pile with a 5.85 mm (0.230 in.) thick GFRP tube was calculated to be higher than the flexural strength of the 508 mm (20 in.) square concrete pile prestressed with fourteen, 12.7 mm (0.5 in.) strands, as shown in Figure 5.23.
- Calculations show that the composite pile fails in bending by fracture of the GFRP tube on the tension side, while the prestressed concrete pile fails by

yielding of the strands in tension, followed by crushing of the concrete in compression.

- The lateral load field tests on both the composite and prestressed piles showed similar behavior to that obtained from laboratory flexural tests and analysis.
- The lateral load versus deflection response for the composite pile was predicted with good accuracy using conventional procedures typically used for prestressed concrete piles.
- Similar pile-to-cap beam connections were used for the composite and prestressed concrete piles, including eight No.7 steel dowels embedded 457 mm (18 in.) inside the piles from one end and extending 762 mm (30 in.) into the cap beam. The piles themselves were embedded 152 mm (6 in.) inside the cap beam.
- Concrete-filled FRP tubes were successfully installed as piling for a bridge pier at the Route 40 bridge. To date, no indications of unsatisfactory performance have been reported.

11.2.5 Field Tests at the Route 351 Bridge

A test pile program was conducted to permit direct comparison of the axial and lateral load behavior of three test piles: 1) a conventional, 610 mm square, prestressed concrete pile, 2) a 622 mm diameter composite pile formed of an FRP shell and filled with concrete and steel reinforcing bars, and 3) a 592 mm diameter composite pile formed of a polyethylene plastic matrix with steel reinforcing bars. Laboratory tests were performed on the pile materials, and the axial and bending stiffnesses of the piles were calculated. The piles are all about 18 m long. The soil at the test site consists primarily of medium dense silty sand, but with a layer of stiff sandy clay located about 1 to 3.5 m above the pile toes. The field testing program included dynamic measurements with CAPWAP analyses, static axial load tests, and static lateral load tests.

Based on the testing, analysis, and construction experience, the following conclusions and observations were made:

- The axial stiffness, EA , of the prestressed concrete pile and the FRP pile are similar to each other and about $2\frac{1}{2}$ times the axial stiffness of the plastic pile.
- Over a working range of bending moments, the flexural stiffness, EI , decreases in order from the prestressed concrete pile to the FRP pile to the plastic pile.

- All three piles exhibited substantial set-up after installation based on comparisons of Case Method capacities at the end of initial driving and restrike five days later, as well as comparisons of CAPWAP analyses of restrike and static axial load tests several days after restrike.
- Applying Davisson's failure criterion to the static axial load tests, the axial capacities were 3090, 2260, and 2130 kN for the prestressed concrete pile, the FRP pile, and the plastic pile, respectively.
- When evaluated at the Davisson failure load, the average unit shaft resistances are 61.8, 46.9, and 48.9 kPa for the prestressed concrete pile, the FRP pile, and the plastic pile, respectively, and the corresponding unit toe resistances are 1854, 2564, and 2339 kPa.
- The prestressed concrete pile exhibited a geotechnical capacity slightly above the mid-point between the capacities calculated using the LCPC CPT methods for steel and concrete piles of the same geometry as the test pile. The FRP and the plastic piles exhibited geotechnical capacities much closer to the LCPC calculations for steel piles than for concrete piles of the same geometries as the test piles.

11.2.6 Axial analyses

The axial capacities of the three test piles were predicted using static analysis methods commonly employed in practice. The methods employed were the Nordlund method, the API method, the LCPC method, and the Imperial College method. The various methods used to predict axial pile capacity led to ratios of calculated to measured pile capacities ranging from 0.70 to 1.14 for the prestressed concrete pile, and from 0.81 to 1.33 for the composite piles. It was found that the level of accuracy of the predictions was comparable for all three test piles.

The prediction results seem to indicate that conventional static analysis methods are applicable to composite piles. However it is the author's opinion that additional case histories are needed to corroborate and extend this conclusion to other composite pile types and to different soil conditions.

The load-settlement behavior was predicted using t-z analyses. A series of these analyses were carried out to determine the adequacy of this method to analyze axially loaded composite pile types such as the ones studied in this research project. The analyses were

completed using empirical load transfer curves available in the literature (e.g., API 1993, and Vijayvergiya 1977), and using theoretically derived load transfer curves.

The predictions using the empirical load transfer curves showed reasonable agreement with the field measurements for the composite piles. The predictions for the prestressed concrete pile showed less agreement and tended to underestimate the measured pile capacity. This could be related to the value of the interface friction angle used. The calculations were based on the interface friction angle measured in the lab, which may be inadequate to represent the field conditions experience by the pile, e.g., in the field the pile interface experienced much larger relative displacements compared to the 0.5 inches used in the laboratory.

The predictions obtained using the theoretically derived load transfer curves were in very good agreement with the measured field behavior. However, the values of the coefficient of horizontal earth pressures, K , which resulted in the best matches with field behavior, were 1.25, 1.0, and 0.9 for the prestressed concrete, FRP, and plastic piles, respectively. The differences in the K coefficient values are contrary to the expected outcome. The expected outcome was to have similar K values for the three test piles since they were installed in similar soil conditions, and they all are full displacement piles with similar cross sectional dimensions. It is possible that this is again related to the δ values measured in the laboratory not being representative of field conditions, perhaps due to the small displacements used in the lab of only 0.5 inches.

The prediction results seem to indicate that conventional t-z analyses are applicable to composite piles. However it is believed that additional case histories are needed to corroborate and extend this conclusion to other composite pile types and to different soil conditions.

11.2.7 Lateral analyses

A series of p-y analyses were carried out to determine the adequacy of this method to analyze laterally loaded composite piles, such as the ones studied in this research project.

A derivation of the governing differential equation for the lateral loaded pile problem was presented and possible limitations when analyzing composite piles were discussed.

The importance of considering shear deformations in lateral pile analyses was discussed. The impact of shear deformations increases with increasing E/G ratios, and decreases with increasing slenderness ratios (L/D). For the test piles tested in this research, the error associated with neglecting shear deformations is estimated to be less than 2.5%.

The importance of including nonlinearity of the flexural stiffness was discussed and illustrated with analyses results.

The results of the p-y analyses using published p-y curves embedded in the LPILE 4.0M program showed reasonably good agreement with the field measurements.

The initial modulus of the p-y curves was found to increase with depth at the highest rate for the FRP pile, at an intermediate rate for the plastic pile, and at the lowest rate for the prestressed concrete pile. This outcome is not as expected, and the reason for the difference in initial modulus values is not known.

Although the analysis results seem to indicate that conventional p-y analyses are applicable to composite piles, additional case histories are needed to determine what factors govern the appropriate value of initial p-y modulus for different pile types in various soils.

11.2.8 Long Term Monitoring

A long term monitoring program has been implemented at the Route 351 bridge project to compare the long-term performance, load transfer, and durability characteristics of an FRP composite pile and a standard prestressed concrete pile. The two production piles selected for monitoring were installed at the centers of Piers 10 and 11.

The field testing of the instrumented production piles included PDA, CAPWAP, and PIT tests. The following conclusions can be drawn from this test program:

- The FRP composite pile and prestressed concrete pile performed similarly during pile driving, as demonstrated by the driving records, PDA traces, measured wave speed generated by the driving hammer, and measured compressive and tensile stresses.
- Both instrumented production piles showed similar estimated pile capacities using the Case Method on pile restrike blows.
- CAPWAP analyses at pile restrike showed similar estimated pile capacities, and high shaft capacity components. The shaft capacities were estimated as being 82% and 71% of the total capacity, for the prestressed concrete and FRP composite piles, respectively. Based on the CAPWAP analyses, the pile capacities were estimated to be more than twice the axial design load of 890 kN.
- No discernable damage was detected in the piles after installation, based on PIT testing performed on the piles before and after pile driving.

Load transfer instrumentation was installed in both piles. Durability instrumentation was installed on the FRP composite pile to monitor the inside and outside strains of the FRP tube. The bridge is still under construction, and monitoring data of the piles is limited to date, therefore no conclusions can be drawn at this time regarding the long term performance of concrete-filled FRP composite piles.

11.2.9 Cost information of composite piles

Composite materials have attractive features such as high resistance to corrosion, high strength to weight ratios, and the possibility of being used in infrastructure projects without maintenance or with low maintenance (Meiarashi et al. 2002). Recent studies have found that the reduced weight of bridge decks made of FRP composite materials have resulted in cost effective bridges due to the reduction of both the construction periods and the cost of the bridge superstructure (Ehlen 1999). The economical competitiveness of composite piles needs to be assessed. To help provide data for such assessments, cost information for the composite piles and prestressed concrete piles used in this research project was compiled and presented.

The initial costs of the composite piles studied in this project were found to be higher than the initial unit costs for prestressed concrete piles. The initial unit costs of the installed composite piles at the Route 40 bridge were about 77 % higher than the unit costs for the prestressed concrete piles. The initial unit costs for the composite piles installed at the Route 351 bridge were higher than cost of the prestressed concrete piles by about 289% and 337% for the plastic and FRP piles, respectively.

The cost effectiveness of composite piles is expected to improve with economies of scale as production volume increases, and by considering life-cycle costs of low-maintenance composite piles. Such life-cycle cost analyses should consider the pile life span, the annualized maintenance costs, and the replacement costs of composite piles compared to prestressed concrete piles. The number of years to be used in the life-cycle cost analyses may not only be related to the life span of the piles, but may also be governed by the actual life span of the bridge superstructure, which depends on the rate of superstructure deterioration and changing traffic demands. Life-cycle cost analyses were not performed for this study due to lack of maintenance cost and frequency information.

11.3 RECOMMENDATIONS FOR FUTURE WORK

Based on the findings from this investigation, the following recommendations are made for future work on composite piles:

- Geotechnical studies:
 - Additional full-scale field load test programs are recommended to extend the conclusions of this study to other composite piles and soil types. Well documented field loading tests of composite piles are scarce, and this lack of reliable database may be one reason that composite piles are not in widespread use for load bearing applications. Therefore, a need to increase the database of instrumented load tests of composite piles is still important.
 - Finite element analyses are recommended to model the field tests on the test piles. This type of analysis takes into account the continuous nature of the soil deposits, as opposed to the t-z and p-y approaches used in this study. Comparison of the results from the different analysis approaches would be useful.
 - Laboratory studies involving lateral load tests on model or small diameter piles installed in uniform and controlled soil conditions may be useful to study the influence that pile characteristics and flexural stiffness have on p-y curves.
 - Assess the level of pile damage, if any, after pile driving by excavating the piles. Visual inspections of the retrieved piles will permit assessing changes in the pile surface due to scratching and scraping of the outer surface. The conclusions drawn from the laboratory interface study regarding the influence of surface roughness and hardness characteristics on interface friction behavior at relatively small displacements may not be applicable to real piles that may experience severe surface wear during pile installation.

- Durability studies:
 - Durability studies involving small diameter concrete-filled FRP piles may be useful to study the durability of axial and flexural structural capacity. Smaller diameter tubes may allow a larger number of tests at a reasonable cost and within a reasonable time frame. A larger number of tests would permit interpreting the data scatter associated with inherent variability of the material properties.
 - A durability study that includes exposure to salt water and other aqueous solutions representing groundwater conditions in industrial sites is recommended.
 - Other studies recommended include degradation due to UV radiation and exposure to high temperatures, resistance to fire, and corrosion of steel cage in PPI piles.
- Structural tests:
 - Test involving compression, bending, and combined axial and bending loading are recommended to determine the full interaction diagrams of composite piles. To date, limited data is available for the combined loading condition,
 - Determine the influence that temperature has on structural behavior, and the effects that differences in coefficients of thermal expansion of the different pile constituents have on pile performance. For example, for concrete-filled FRP piles, the coefficient of thermal expansion of the FRP tube will be a function of the factors such as fiber and resin type, number of fiber layers, fiber lay-up, fiber volume fraction, etc. If the resulting thermal coefficient of the FRP tube is significantly different from that of the concrete core, it is conceivable that the two materials would debond.
 - Resistance to fire exposure should be investigated. Although the majority of the pile length is embedded in the ground or submerged in water, there is usually a portion of the pile that is exposed. Although the probability of exposure to fire of

piles is low, it could be important for some cases where the piles form part of priority bridge structures that have to survive more severe conditions.

- Additional recommended studies include tests to study the behavior under cyclic loading of composite piles, studies of creep under axial compression, and influence on rate of loading on the pile structural behavior.
- It is recommended that detailed life-cycle cost analyses be performed for different composite pile types and conventional piles.