Plastic Piling in Geotechnical Construction

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SPONSORS
- Federal Highway Administration
- Empire State Development Corporation
- Port Authority of NY & NJ
- Region II Transportation Research Center
Hudson River Park Project, Vision
Hudson River Park Project, Reality
Deterioration of Conventional Piling

- $1 Billion per year
Clean Water Act

- Federal water pollution control act of 1972 caused marine borers to return

PANYNJ Data
Bognacki & Gill, 1997
Recycled Plastics

- 8.4 Billion pounds of rigid plastic containers are produced each year
- 7.2 Billion pounds are land-filled
Environmental Advantages of FRP

- Utilize Recycled Materials
- Eliminates Creosote & CCA
  - Disposal problems
  - Threat to marine life
  - Potential health hazard to workers
- Preserves Old Growth Forests
HDPE Plastic Lumber Recycling Process

RETRIEVED HDPE #2 PLASTIC CONTAINERS → PLANT RECYCLING → EXTRUDED PLASTIC MATERIALS → INSTALLED PRODUCT
Prior Uses of Recycled Plastics in Construction

Lake Placid
Bobsled Deck, NY

Kelley’s Island
Boardwalk, OH
Demonstration Projects

Tiffany Pier, Bronx, NY

New Baltimore Conservancy
Bowstring Truss Bridge
Piling is Different!

- May be damaged during driving
- May creep under sustained heavy loads
- Catastrophic consequences of failure
State of FRP Piling Practice

- A few vendors
- Prototype in Los Angeles in 1987
- Material Cost = 2–3 conventional systems (~Foundation cost = 120% of conventional piling)
- Primarily used to resist ship impact (fendering)
- Made of recycled HDPE with E-glass or steel reinforcement
- Additives and stabilizers to improve performance
Available Products

- Steel Core Piling
- Fiberglass & Pultruded Piling
- Reinforced Plastic Piling
- Wood Composites
- Plastic Lumber
Reinforced Plastic Piling

- Extruded HDPE matrix
- Fiberglass or Steel structural Reinforcement (6–16 bars)
- Additives & Foaming Agent
- D = 25–40 cm
- L = 23 m
- 2 Manufacturers
Designer Concerns Delaying Adoption of FRP Piling

- Lack of long-term record
- Creep
- Cost
- Durability
Engineering Performance

1. Mechanical Properties
2. Durability
3. Design
4. Creep
5. Drivability & Load Tests
1. Mechanical Properties

- Typical Values
- Structural & Material Behavior
- Soil Structure Interaction
- Characteristic Strength
# Typical Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fiberglass</th>
<th>Recycled HDPE</th>
<th>Steel</th>
<th>Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile, MPa (ksi)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>485 (70)</td>
<td>7 (1)</td>
<td>310 (45)</td>
<td>1.4 (0.2)</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>62,000 (9,000)</td>
<td>414 (60)</td>
<td>200,000 (29,000)</td>
<td></td>
</tr>
<tr>
<td><strong>Compressive, MPa (ksi)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ultimate Strength</td>
<td>275 (40)</td>
<td>6.2 (0.9)</td>
<td>310 (45)</td>
<td>27.6 (4)</td>
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<tr>
<td>Compressive Modulus</td>
<td>51,000 (7,500)</td>
<td>310 (45)</td>
<td>200,000 (29,000)</td>
<td>25,000 (3,600)</td>
</tr>
<tr>
<td><strong>Flexural Strength, MPa (ksi)</strong></td>
<td>485 (70)</td>
<td>5.2 (0.75)</td>
<td>310 (45)</td>
<td></td>
</tr>
<tr>
<td><strong>Unit Weight kN/m³ (pcf)</strong></td>
<td>7.9 (50)</td>
<td>7 (45)</td>
<td>77 (490)</td>
<td>24 (150)</td>
</tr>
</tbody>
</table>
Spatial Distribution of Strength in One Pile
Objectives

To assess the spatial distribution of the compressive strength of piling made of foamed recycled plastics.

This may lead to use of coupon specimens for quality control of polymeric piling and plastic lumber.
Seapile™

- Foamed HDPE core
- E-glass reinforcement
- Additives & matrix reinforcement
Methodology

- Unconfined compression test
- Seaward International, Seapile™
- Specimens punched from Seapile’s Core
- Verify lack of a sample size effect
Stress-Strain (1/4” specimens)
Stress Strain (3/8”)

![Stress Strain Graph](image)

- Average Stress (MN/m²)
- Strain %
- R=8.9 cm
- R=7.0 cm
- R=5.1 cm
- R=1.6 cm
- R=3.2 cm
Spatial Distribution of Density

\[ \gamma = 0.5 - 0.0213R + 0.0058R^2 \quad (R^2 = 0.977) \]
\[ \gamma = 0.397e^{0.0703R} \quad (R^2 = 0.94) \]
\[ \gamma = 0.36 + 0.0427R \quad (R^2 = 0.909) \]
Density vs. Strength

Stress at $\varepsilon = 10\%$ (MN/m$^2$)

Density (kN/m$^3$)
Effect of Specimen Size

- △ D = 6.4 mm (1/4")
- □ D = 9.5 mm (3/8")
- ○ D = 12.7 mm (1/2")
- ▲ D = 19.1 mm (3/4")
Data Normalization

Dimensional Analysis
Regression Analysis
Stress Strain Curves for Full Cross Section Derived using Regression Analysis of Coupon Specimens

\[ \sigma = m_0 e^{m_1 R} \]

- R = radius
- \( m_0, m_1 \) are constants
- \( m_0 \) represents strength at origin
  - value is strain dependant
  - secant modulus
- \( m_1 = 0.15-0.18 \) depending on e

Thin lines are for 3/8” specimens
Thick line calculated \( \sigma = m_0 e^{m_1 R} \)
Stress Area Method (SAM) v. Regression Analysis
Dimensional Analysis

- Information about a phenomenon is deduced from the single premise that the phenomenon can be described by a dimensionally correct equation among relevant variables.

- Relevant Variables
  - Stress, \( \sigma \)
  - Unit Weight, \( \gamma \)
  - Radius, \( R \)

\[
\begin{align*}
\left( \gamma^a \right) \left( R^b \right) \left( \sigma^c \right) &= 1 \\
\left( \frac{F}{L^3} \right)^a \left( L^b \right) \left( \frac{F}{L^2} \right)^c &= 1 \\
\left( \gamma^{-1} \right) \left( R^{-1} \right) \left( \sigma^{-1} \right) &= 1
\end{align*}
\]

\[\pi = \frac{\sigma}{\gamma \cdot R}\]
Data Normalization

Characteristic Strength \((\sigma/\gamma R)\)

\(\sigma\) = stress
\(\gamma\) = unit weight
\(R\) = distance from center
Stress Strain of All Specimens

![Stress Strain Graph](image)
Modified Characteristic Strength

\[ \sigma/\gamma(R+K) \]

- 19.1mm, R=8.4cm
- 19.1mm, R=5.7cm
- 19.1mm, R=3.1cm
- 12.7mm, R=8.8cm
- 12.7mm, R=6.8cm
- 12.7mm, R=4.6cm
- 9.5mm, R=9.1cm
- 9.5mm, R=7.5cm
- 9.5mm, R=5.9cm
- 6.4mm, R=9.1cm
- 6.4mm, R=7.5cm
- 6.4mm, R=5.9cm
- 6.4mm, R=4.1cm
- 6.4mm, R=2.5cm

Strain, %
Conclusions

- Strength and density of foamed polymeric piling increased exponentially with distance from the center of the pile.
- Strength is linearly proportional to density and inversely proportional to the local unit weight.
- Stress strain curve for the full cross section was obtained using testing done on coupon specimens.
- $\pi = \sigma / \gamma (R+K)$ represents the stress strain curves of specimen located in the outer segment of the pile ($R>3.5$ cm).
2. Durability in Aggressive Environments

- 12 month study
Accelerated Degradation Methodology

- Seaward International Seapile™
- High temperature incubation of small specimens
- Arrhenius model to extrapolate results to field temperature
  - 3 pHs (acidic, neutral, & basic)
  - 3 temperatures for each pH
  - Unconfined compressive strength
  - 6 specimens for each condition
  - 10% strain
Arrhenius Model

Limitations

- Presumes that reactions can freely occur between all the solid molecules and the aggressive media
- More than one mechanism may cause degradation
- Resins may undergo changes on heating and can become susceptible to more loss or gain in strength
Sample Results

Characteristic Strength ($\sigma/\gamma R$)

Strain, %
Specimens in Water

Increase in characteristic strength of specimens incubated in water!

@ 10% Strain
Specimens in Acid

@ 10% Strain

$(\sigma/\gamma R)$ for pH = 2
$(\sigma/\gamma R)$ for pH = 7

Incubation Time, Hours

Normalized Strength (Acidic/Neutral)
Specimens in Alkaly

@ 10% Strain

\( \frac{\sigma}{\gamma R} \) for pH = 1

\( \frac{\sigma}{\gamma R} \) for pH = 7
Arrhenius Plot (Acidic)

Remaining Strength @ 10% Strain
Remaining Strength @ 10% Strain

Arrhenius Plot (Alkali)
Performance at Field Temperature

Remaining Relative Strength @ 25°C

@ 10% Strain Relative to specimens in water

Time, Years

Resistance Defined at 10% Strain Curve DOES NOT Account for Effect of Aging Relative to Specimens Incubated in pH = 7

Acidic (pH=2) Alkaline (pH=12)
3. Creep Behavior

- Thermal Acceleration
- Energy Approaches
Creep Prediction Methods

- Thermal Methods based on Arrhenius Equation
  - Take advantage of the similarity between the effect of temperature and time on the creep behavior of materials
    - TTS (Time-Temperature Superposition).
    - SIM (Stepped Isothermal Method).

- Energy Methods
  - Extrapolate the relationship between two stress-strain curves one performed at a rate several log cycles slower than the other to obtain the creep behavior of the material
    - SED
Thermal Methods

- According to Arrhenius Equation elevating temperature is equivalent to increasing the strain rate.
- The shift factor for elevated temperature can be calculated for some homogeneous polymeric material according to well known universal constants (in chemistry).

\[ \log a_T = \frac{c_1(T - T_0)}{(c_2 + T - T_0)} \]

<table>
<thead>
<tr>
<th>Temperature</th>
<th>24°C (72°F)</th>
<th>38°C (100°F)</th>
<th>49°C (120°F)</th>
<th>60°C (140°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_T)</td>
<td>1</td>
<td>5.26</td>
<td>14.45</td>
<td>33.12</td>
</tr>
</tbody>
</table>
TTS @ 400 psi (Virgin HDPE)

Conventional Creep

Master curve after Application of Shift Factors
TTS on Virgin HDPE

- Two different sizes of virgin HDPE.
  - Consistently good results for D=1.5”
- The results of TTS show that this method is applicable for compressive creep prediction.
- The shift factor for HDPE is Approximately 33 for 60°C.
  - 1 day at 60°C ⇒ 33 days at 24°C.
  - 50 years life at 24°C requires 1.5 years at 60°C
- Maintaining Elevated temperature creep test
  - Difficult
  - Changes in material properties
Stepped Isothermal Method (SIM)

- Only one specimen is used
- Based on ASTM test method for tensile creep of geosynthetics
- Eliminates scatter due to specimen variability
Results require a great deal of judgment and are highly user dependent
Extrapolation of Thermal Results

Assuming that there is no rupture creep stage for these stress levels the results can be extrapolated for a longer time span.
Comparison of SIM & TTS with conventional creep

HDPE loaded in compression will creep by approximately 2% in 100 years when loaded at 400 psi (2759 kPa)
Strain Energy Density Method

- Any point on a stress strain curve has a corresponding point on a different stress strain curve conducted at a different strain rate so that the two points have the same energy density and satisfy the equation.
- Based on conservation of energy.
- Equal strain energy

\[ \sigma_1 \varepsilon_1 = \sigma_2 \varepsilon_2 \]

\[ \left( \frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2} \right)^m = \frac{\sigma_1}{\sigma_2} = \frac{\varepsilon_2}{\varepsilon_1} \]
Strain Energy Density Method

- An exponential relationship is assumed for points having equal strain energy density (1)
- Compute $m$ for any 2 reference stress strain tests corresponding to points having equal strain energy density (2)
- Assuming the modulus of elasticity, $E$, changes with the rate of loading, but remains a constant for any particular strain rate, the term $m$ would also be a constant number that does not depend on the strain energy density.

$$\left(\frac{\dot{\varepsilon}_r}{\dot{\varepsilon}_r'}\right)^m = \frac{\varepsilon_r'}{\varepsilon_r} \quad (1)$$

$$m = \frac{\log\left(\frac{E_{r1}}{E_{r2}}\right)}{2 \log\left(\frac{\dot{\varepsilon}_r}{\dot{\varepsilon}_r'}\right)} \quad (2)$$

- Creep is assumed to be as a very low strain rate process.
- The stress strain behavior of material can be extrapolated for any strain rate.
Variation of $m$ with Respect to the Order of Magnitude in Reference Strain Rates for Virgin HDPE

$m$ can be computed for any pair of strain rates $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$.

$m$ converge to a unique number as the order of magnitude of strain rates between different pairs increases.

$$\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)^m = \sqrt[2]{\frac{E_{r1}}{E_{r2}}} \quad \Rightarrow \quad m = \frac{\log\left(\frac{E_{r1}}{E_{r2}}\right)}{2 \log\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)}$$
SED Method… cont.

- A creep stress, $\sigma_c$, is selected for computation.
- A time is selected for computing the corresponding creep strain, $t_i$.
- The stress strain test having the slower of the two strain rate is selected as a reference for further calculations.
- The strain rate of the imaginary equivalent - creep stress-strain (iECSS) test, corresponding to the creep time of interest is computed using Eq. 3.
- The strain on the iECSS corresponding to creep, $\varepsilon_i$, can be calculated from the strain rate, using Eq. 4.
- Creep strain is taken as half of $\varepsilon_i$, (Eq. 5) to account for the fact that creep stress is constant but in iECSS the stress varies.

\[
\dot{\varepsilon}_t = \frac{2m+1}{\sqrt{E_r \times t_i}} \sigma_c \times \dot{\varepsilon}_r^{2m} \tag{3}
\]
\[
\varepsilon_i = \dot{\varepsilon}_t \times t_i \tag{4}
\]
\[
\varepsilon_c = \frac{\varepsilon_i}{2} \tag{5}
\]
Stress-Strain on Recycled HDPE
Obtain Modulus of Elasticity for each rate of loading

- Stress Rate 0.003%
  - $E = 101810$
  - $R^2 = 0.9954$

- Stress Rate 0.03%
  - $E = 111020$
  - $R^2 = 0.9913$

- Stress Rate 3%
  - $E = 148380$
  - $R^2 = 0.9976$

3%
0.003%
Comparing SED, SIM, & TTS for Virgin HDPE
Comparing SED, SIM, & TTS for Recycled HDPE

SED
SIM
Conventional Creep
Conclusions of Creep Study

- Accelerating compressive creep of HDPE is viable.
  - **TTS:** Easy, but polymer changes due to incubation temperature limits acceleration to a factor of 30.
  - **SIM:** Uses one specimen only, thus overcoming specimen variability of recycled polymer, but procedure is user dependent.
  - **SED:** Holds most promise. Can be used to predict onset of tertiary creep.

- All approaches yielded estimates consistent with conventional creep tests.
4. Design

- Geotechnical capacity
  - Interface Friction
  - Bearing Capacity

- Structural Capacity
Interface Friction

- **Fiberglass**
  - Pando et al, 2002
    \[ \delta_{\text{Fiberglass}} = 60-90\% \text{ of } \delta_{\text{Concrete}} \]
  - Frost, Han, 1999
    \[ \delta_{\text{Fiberglass}} \geq (10\%) \delta_{\text{Steel}} \]

- **HDPE**
  - Research on Geosynthetic Liners
  - \( \delta = 8-15^\circ \)
  - Partial slippage along pile shaft during loading?
Bearing Capacity

- No foreseeable difference
Soil Structure Interaction

- Low Stiffness
  - Advantageous in fendering
  - Differential settlement in bearing

- Modulus is Load & Time Dependent
  - Effect of creep on load transfer?
  - Time dependant load shedding?
Structural Behavior

- **Low Stiffness**
  - Difficult to install & handle
  - Suitable for fender piling
  - Dampen seismic forces transferred to structure
  - Reduce moments in piled rafts

- **Variation in Properties → FOS?**
  - Unit weight
  - Strength

- **Viscoelastic Creep**
Buckling

“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”

Han & Frost, 1999
5. Driveability

- Concerns
- WEAP
- Demonstration
Driveability Concerns

- Less Efficient Driving
  - High damping
  - Low stiffness

- Integrity
  - Localized low strength
Calibrate WEAP for FRP Piling

- Input parameters are obtained by back analyses of case histories
  - Reduce modulus
    - 33% for reinforced plastic piling
  - Adjust damping
    - 9 for reinforced plastic piling
    - 5 for steel core piling
  - Residual stress analysis (RSA)
Effect of Residual Stress Analysis

- **Steel**
  - Vulcan 1
  - Rated 20 kJ (15 kip-ft) and an
  - Enthru= 11 kJ (8 kip-ft)

- **HDPE**
  - Vulcan 12
  - Rated 53 kJ (39 kip-ft)
  - Enthru=28.5kJ (21 kip-ft)

Failure to use RSA will result in a need for a bigger hammer.
Effect of Modulus of Elasticity on WEAP Results

- Blows corresponding to a fixed capacity is plotted.
- Damping ratios and specific weights kept constant.

- Drivability of conventional piles depends on soil properties.
- Drivability of polymeric piles depends on BOTH soil & pile properties.
Effect of Selected Unit Weight on WEAP Results

- Blows corresponding to a fixed capacity are plotted.
- Damping ratios and Modulus kept constant.
- Because of foaming, the unit weight varies within the cross section and from one pile size to another.
Effect of Damping Ratio on WEAP Results

- Damping = 0.02R_d (EA/c)
  - EA/c is pile impedance
  - E = modulus
  - A = area
  - C = compression wave velocity in
  - R_d = input damping
    - 1 for steel,
    - 3 for concrete
    - 5 for timber
**Effect of Hammer Type**

Single Acting Hammer
- The dynamic force exerted is shorter in duration than a diesel hammer
- Heavier rams and shorter strokes
- Stroke and efficiency are not dependent on the soil/pile stiffness

Reinforced plastic pile
- Vulcan 20, enthru = 42.5 kJ (31.5 kip-ft)
- Delmag 12 diesel, enthru 40.5 kJ (30 kip-ft)
Parametric Studies Using WEAP

Blows per Foot

Capacity, kN

Capacity, kips

Reinforced Plastic
Fiberglass Tube
Timber

Estimated Geotechnical Capacity

Very Soft Organic Silt
Medium Stiff Clay
Dense Sand
Parametric Studies Using WEAP

Estimated Geotechnical Capacity
Field Demonstration

- Installed 14 piles in Port Newark
  - $L = 60$ ft
  - $D = 16$ in
- 5 manufacturers
- Dynamic Monitoring
- Load tests on instrumented piles
Driveability - Seaward
Driveability - PPI
Driveability - Plastic Lumber

- Successful Driving
  - L = 20 ft, D = 16 in
  - L = 12 ft, D = 10 in
Driveability - Lancaster
Load Tests

- Lancaster Composites
- Seaward International
- Plastic Piling Inc
- American Echo Board
Load Test
Lancaster Composites

- Concrete Filled Fiberglass Tubing
- D = 16 in
- L = 60 ft

Settlement, inches

Load, Ton
Load Test
Plastic Piling Inc

- Steel Reinforced Polymer (HDPE) Matrix
- D = 16 in
- L = 60 ft
Load Test
Seaward International

- Fiberglass Reinforced Polymer (HDPE) Matrix
- $D = 16$ in
- $L = 60$ ft
Load Test American Echo Board

- Plastic Lumber
- D = 16 in
- L = 20 ft x 2

Trimax Piling 100
Summary of Load Tests
Conclusions

- FRP Piling is Viable
- Advantages
  - Environmental benefits
  - Durability
- Disadvantages
  - Cost
  - Lack of long term record
  - Compressibility & low modulus
  - High variation in material properties
Rebuilding after Katerina

- Coastal communities are now required to build above the Advisory Base Flood Elevations.
- May result in structures being elevated by as much as 25 feet above ground level,
- Polymeric piling is unlikely to be attacked by termites, which feed on exposed timber piling.
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THANK YOU

Tiffany Pier, Bronx, New York
Transparent Soils

- To visualize the behavior of soils & foundations using transparent soil models
Transparent Soils, Cont.

Transparent Soil Model

Digital Camera

Line Generator

Laser Source

Diagram showing a setup with labeled components.
Transparent Soils, Cont

Before

Analysis Results

After
Monitoring of Structures Distressed by Earth Pressure
Non Destructive Testing (NDT) of Drilled Shaft Defects & Their Effect on Capacity
Typical Results (Shaft 4)

- Voids & soil inclusions
- 5–45% of cross section

<table>
<thead>
<tr>
<th>Shaft 4</th>
<th>As Built</th>
<th>NDT Testers - Testing Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth, m (ft)</td>
<td>No.</td>
<td>Legend</td>
</tr>
<tr>
<td>1.5 (5)</td>
<td>A</td>
<td></td>
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<tr>
<td>3.0 (10)</td>
<td>B</td>
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<tr>
<td>4.6 (15)</td>
<td>C</td>
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<tr>
<td>6.1 (20)</td>
<td>D</td>
<td></td>
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<tr>
<td>7.7 (25)</td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>9.2 (30)</td>
<td>F</td>
<td></td>
</tr>
<tr>
<td>10.7 (35)</td>
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<td>12.2 (40)</td>
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<td>13.7 (45)</td>
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<td>15.2 (50)</td>
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