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Sustainable Piling

Made of Recycled Polymers, A State of The Art Review

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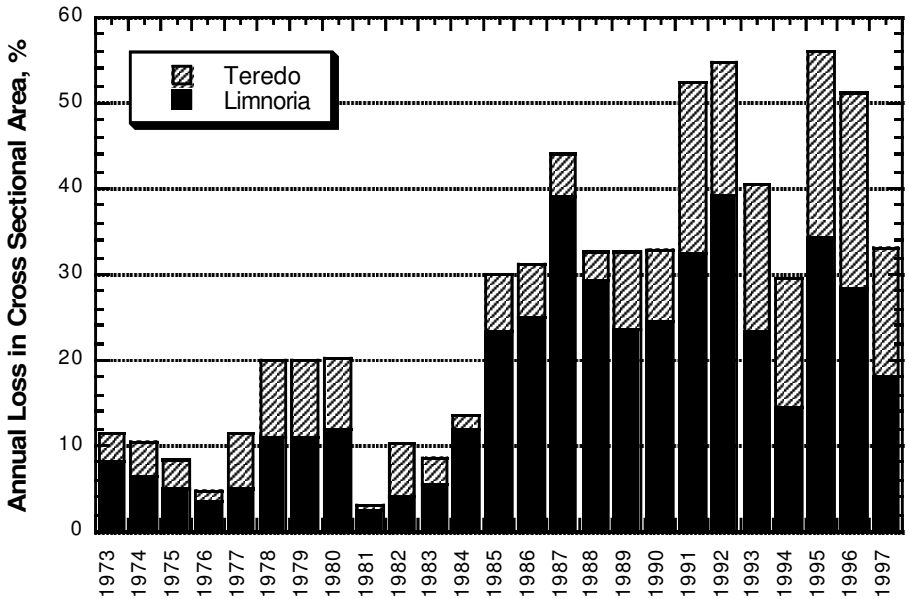
Deterioration of Conventional Piling

- $1 Billion per year

Clean Water Act

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



PANYNJ Data
Bognacki & Gill, 1997

Environmental Advantages of FRP

- Utilize Recycled Materials
  - 12 million tons of rigid plastic containers are produced each year
  - 75% are land-filled
- Eliminates Creosote & CCA
  - Disposal problems
  - Threat to marine life
  - Potential health hazard to workers
- Preserves Old Growth Forests

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Prior Uses of Recycled Plastics in Construction

Lake-Placid Bobsled Deck, NY

Demonstration Projects

New Baltimore Conservancy
Bowstring Truss Bridge

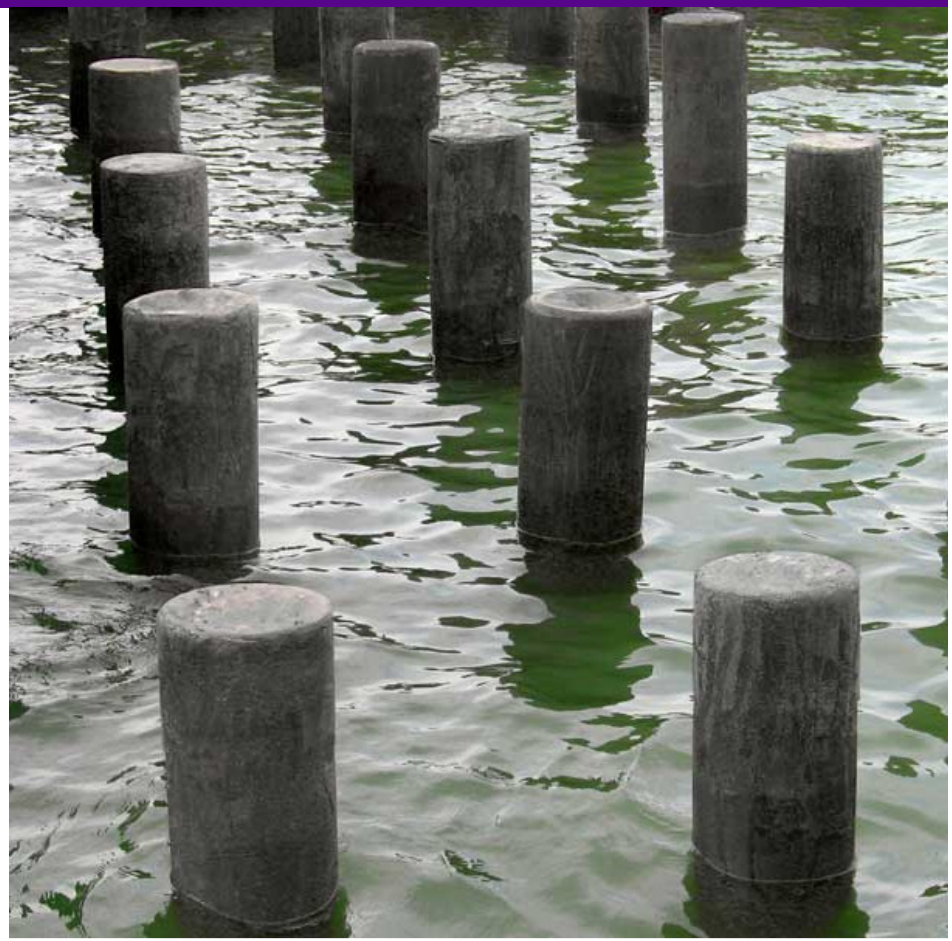
Tiffany Pier, Bronx, NY

Piling is Different!

- May be damaged during driving
- May creep under sustained heavy loads
- Catastrophic consequences of failure

State of Polymeric Piling Practice

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



Reinforced Plastic Piling

- Extruded HDPE matrix
- Fiberglass or Steel structural Reinforcement (6–16 bars)
- Additives & Foaming Agent
- D = 25–40 cm
- L = 23 m

Plastic Lumber

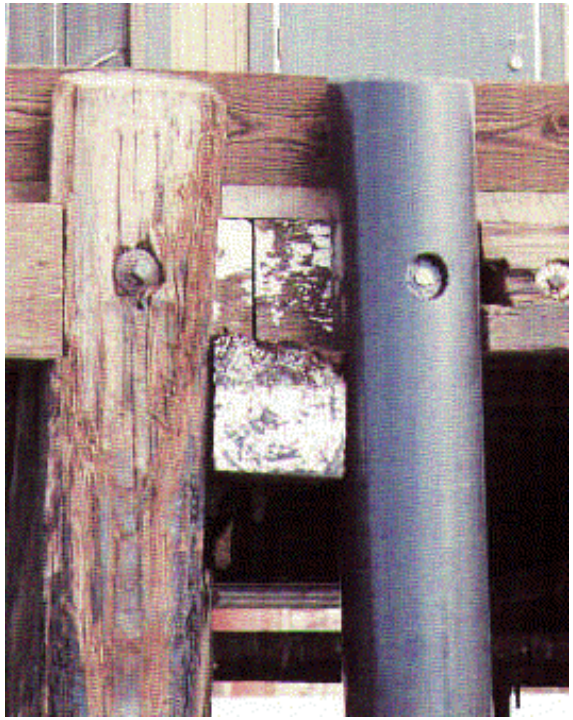
- Recycled HDPE
- 20% Fiberglass
- Foamed
- D = 25–40 cm
- Length up to 7 m

Designer Concerns

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

Engineering Performance

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

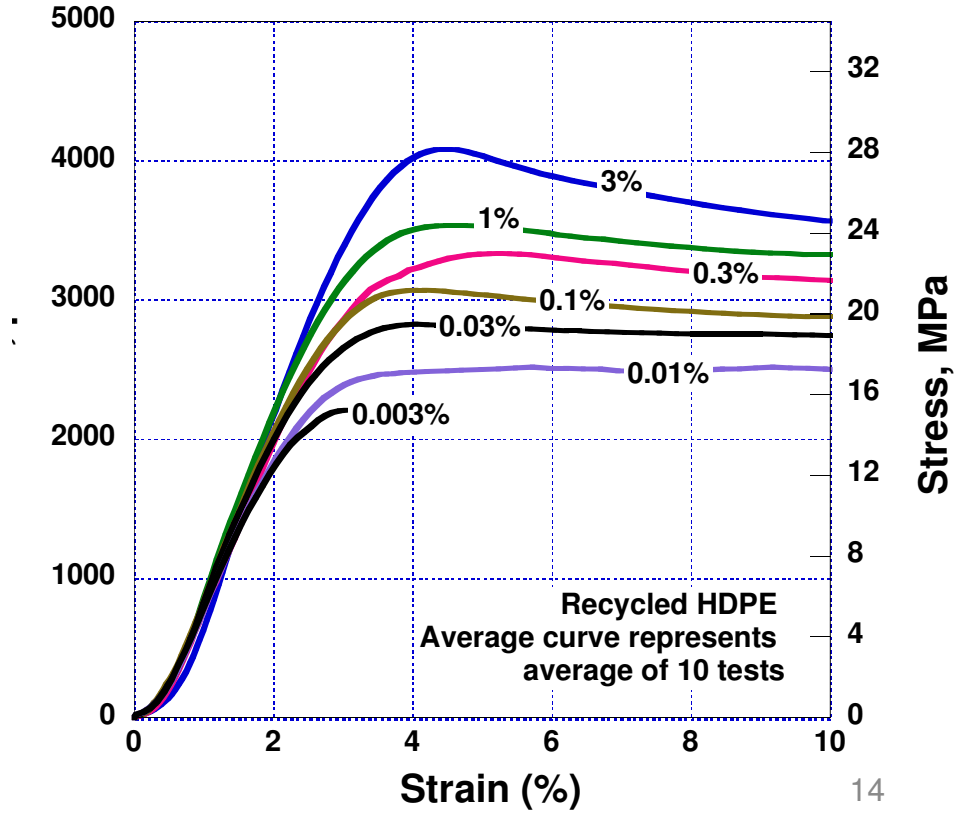


1. Typical Mechanical Properties

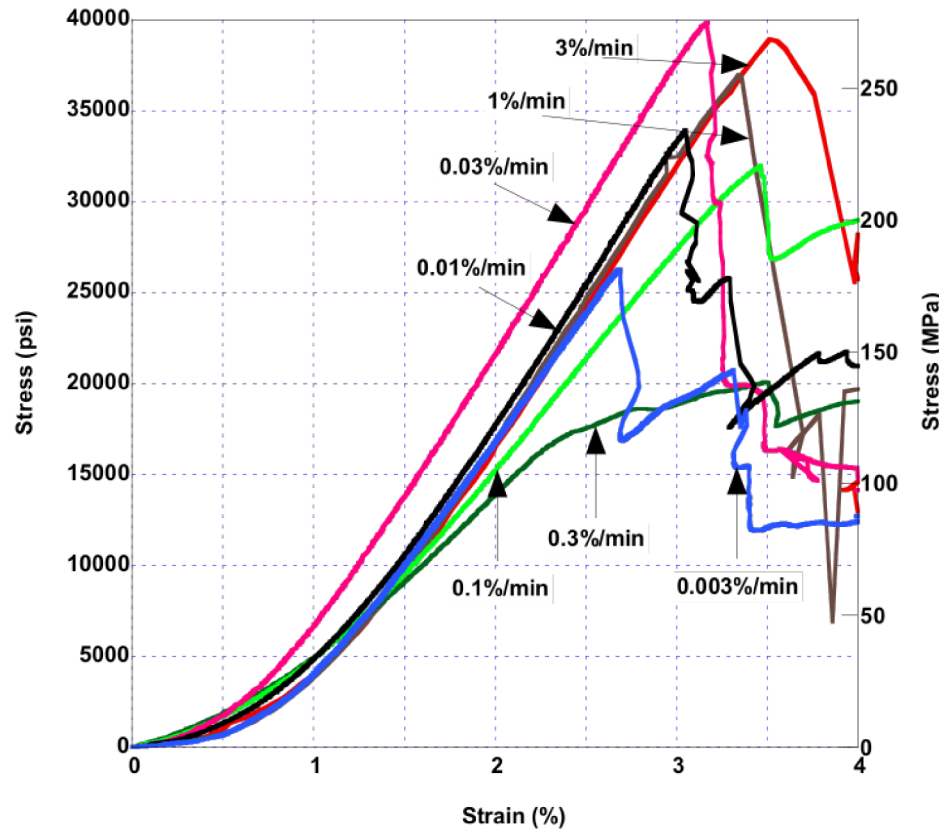
Parameter	Fiberglass	Recycled HDPE	Steel	Concrete
Tensile, MPa (ksi)				
Ultimate Strength	485 (70)	7 (1)	310 (45)	1.4 (0.2)
Tensile Modulus	62,000 (9,000)	414 (60)	200,000 (29,000)	
Compressive, MPa (ksi)				
Ultimate Strength	275 (40)	6.2 (0.9)	310 (45)	27.6 (4)
Compressive Modulus	51,000 (7,500)	310 (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)

Stress-Strain Behavior of Recycled HDPE

- Strain rate shown next to curve
- Each curve is the average of 10 individual stress strain
- Stress Strain of Recycled HDPE Depends on Strain Rate



Stress-Strain Behavior of FRP Reinforcement



Strain rate shown next to curve

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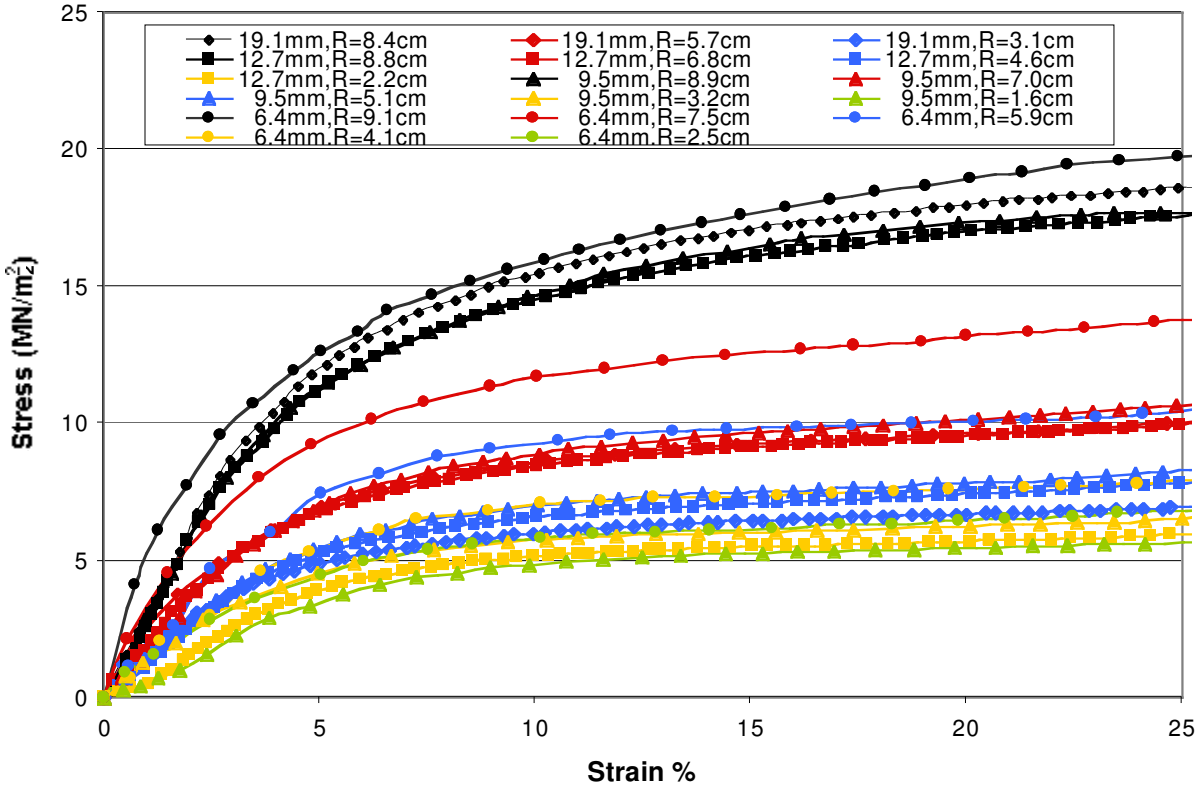
Spatial Distribution of Strength of Recycled HDPE in One Pile



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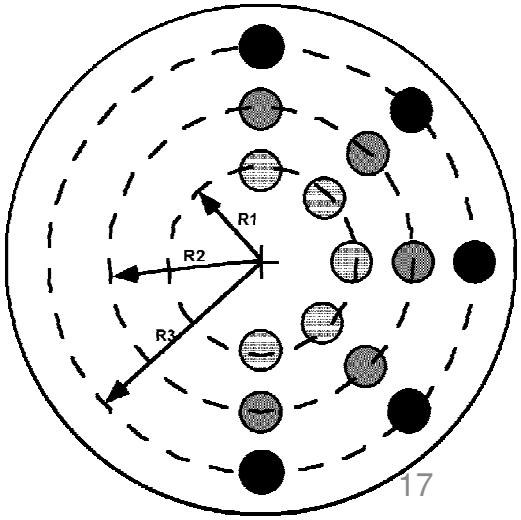
Spatial Distribution of Compressive Strength in Foamed Recycled HDPE

- Unconfined compression test
- Seapile™

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



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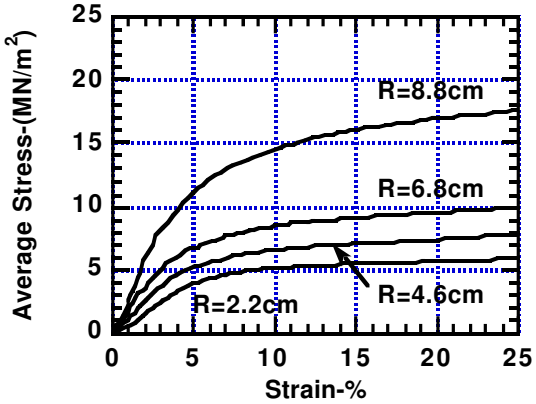
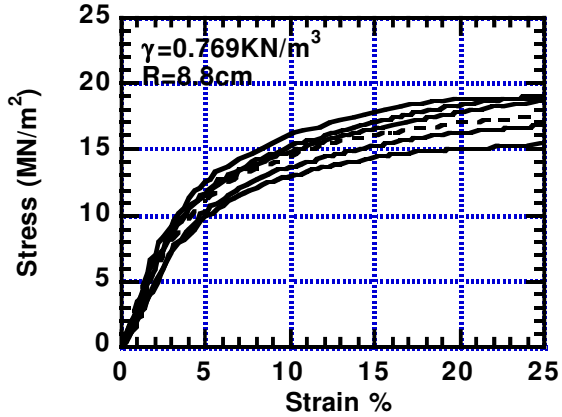
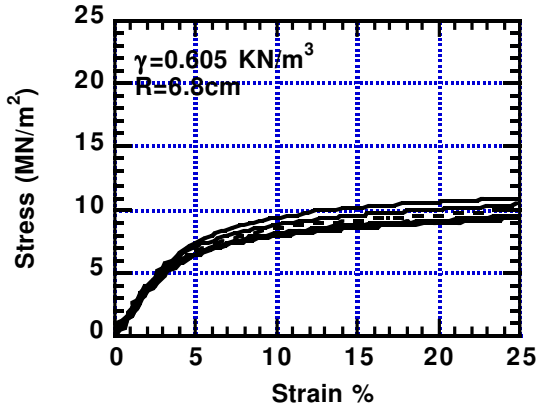
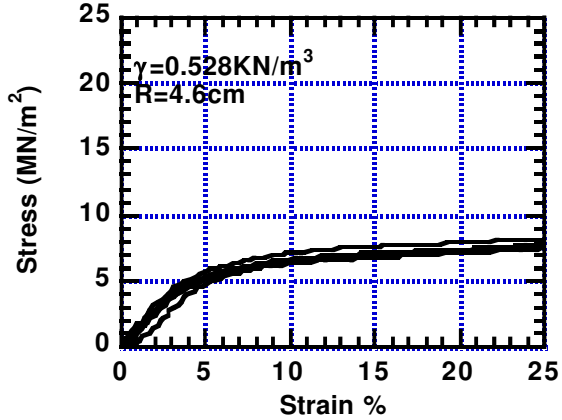
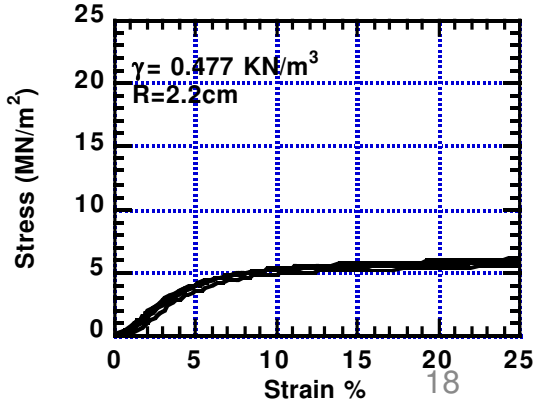
Stress-Strain (1/4” specimens)



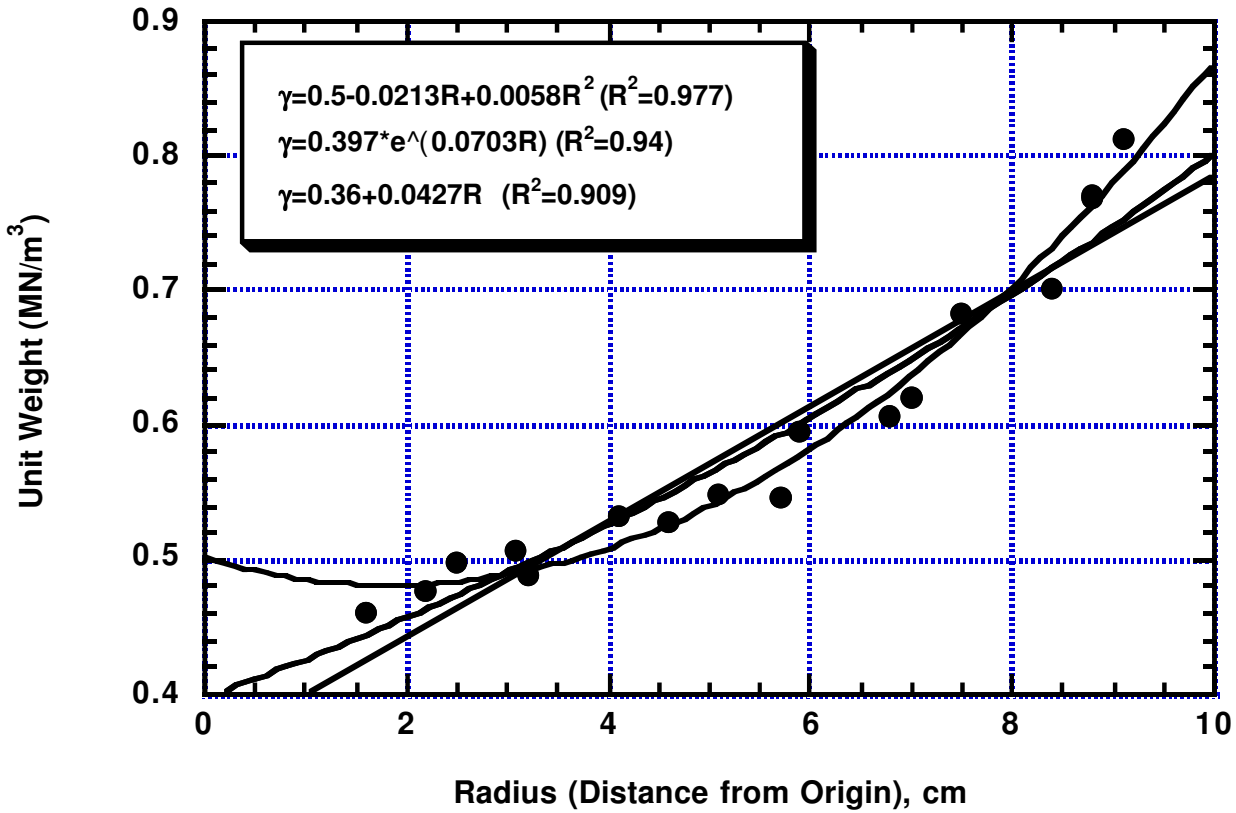




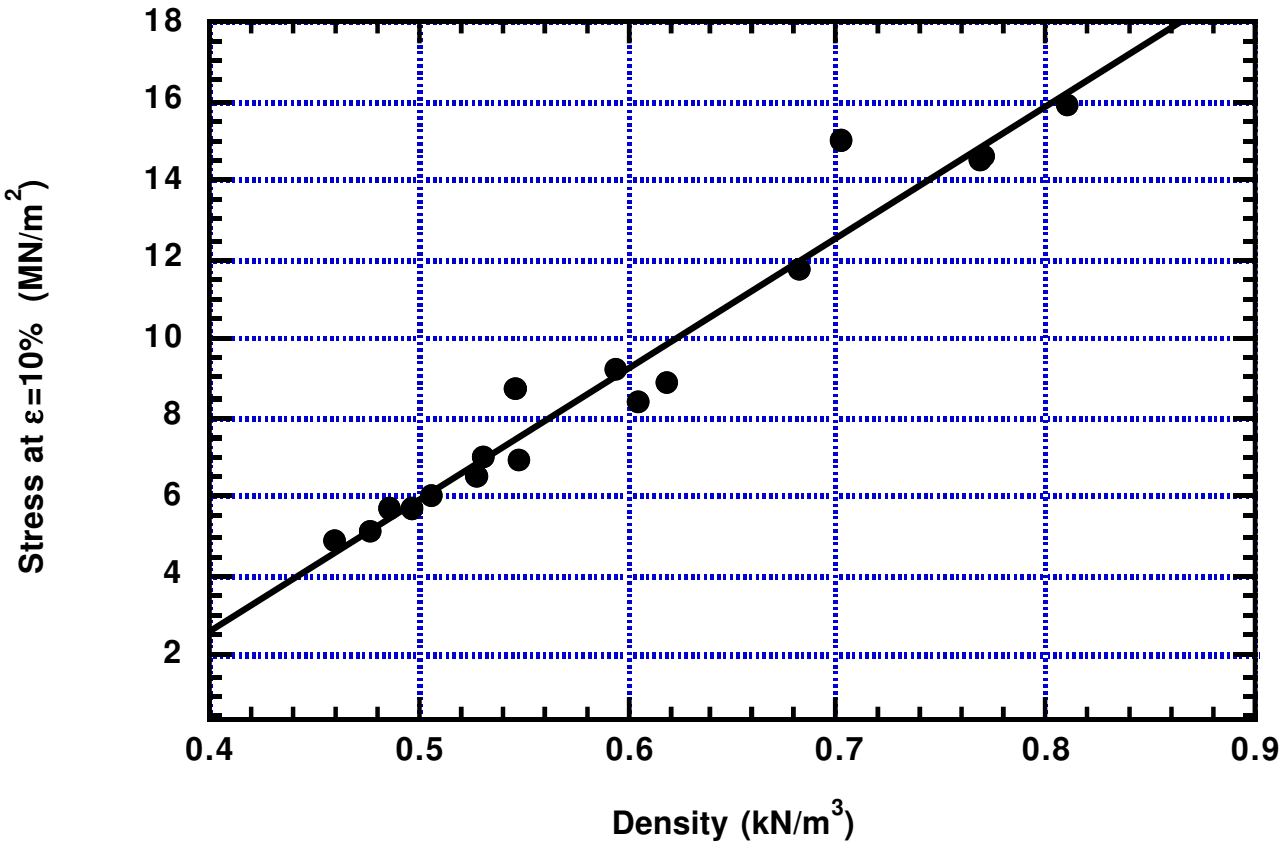




Spatial Distribution of Density



Density vs. Strength



Data Normalization

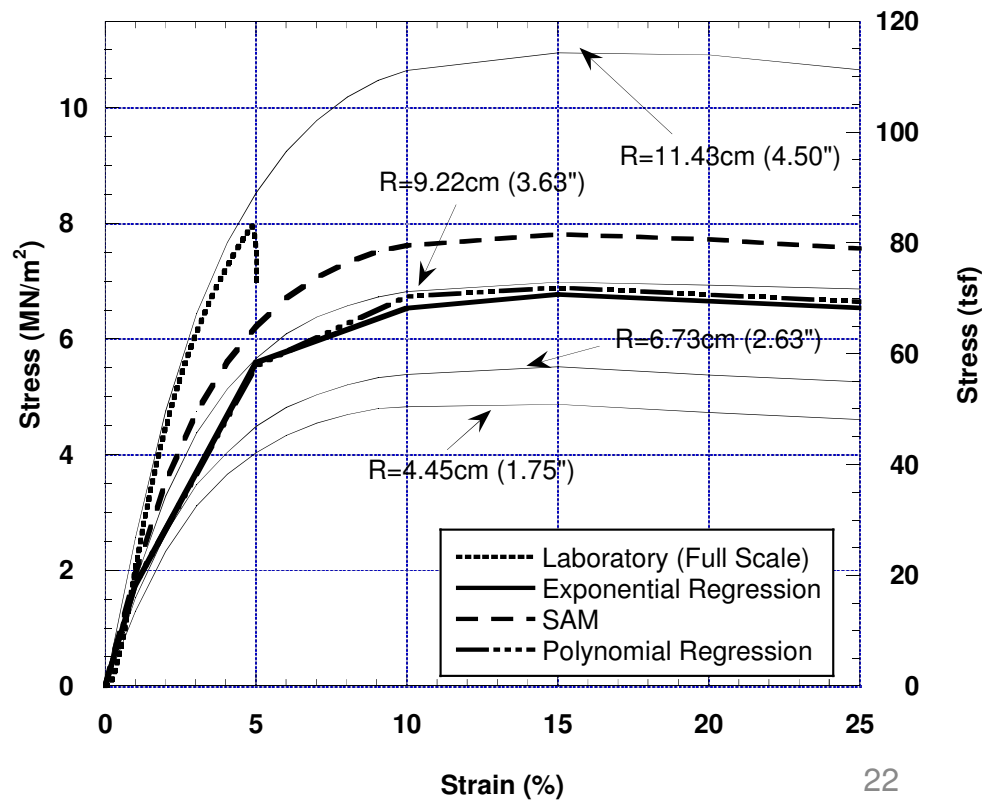
- Dimensional Analysis
- Regression Analysis

Stress Strain Curves for Full Cross Section using Coupon Specimens.

$$\sigma = m_0 e^{m_1 R}$$

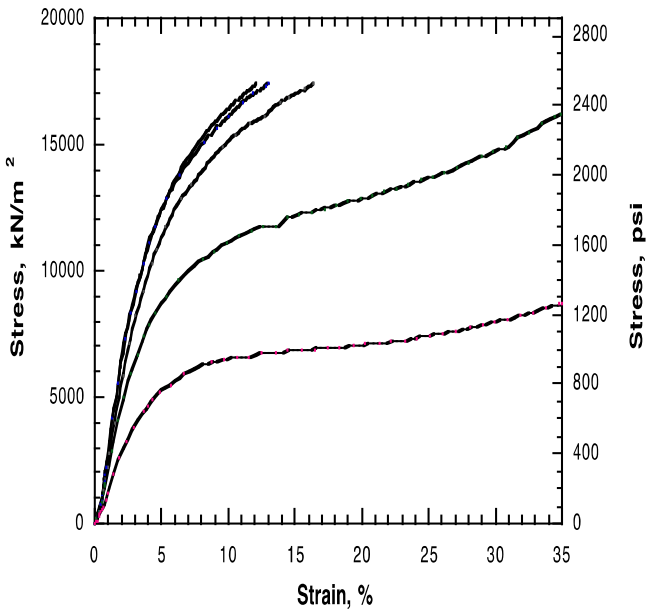
Exponential Regression

- **R = radius**
- **m_o, m_1 are constants**
- **m_o represents strength at origin**
  - value is strain dependent
  - secant modulus
- **m_1 = 0.15–0.18 depending on e**



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.

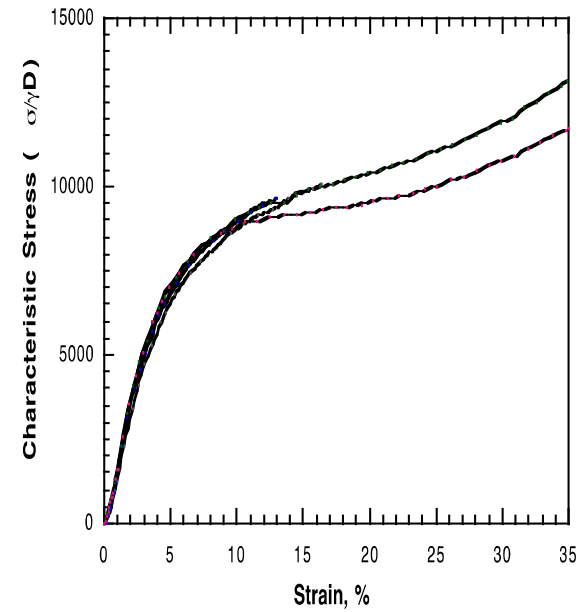


$$(\gamma)^a (R)^b (\sigma)^c = 1$$

$$\left(\frac{F}{L^3}\right)^a (L)^b \left(\frac{F}{L^2}\right)^c = 1$$

$$(\gamma)^{-1} (R)^{-1} (\sigma)^1 = 1$$

$$\pi = \frac{\sigma}{\gamma \cdot R}$$



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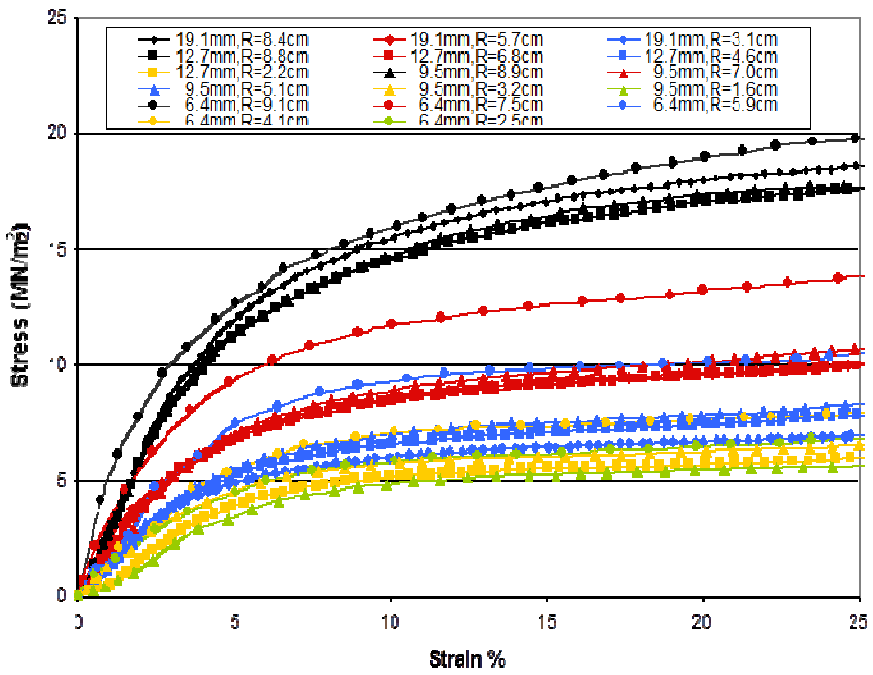
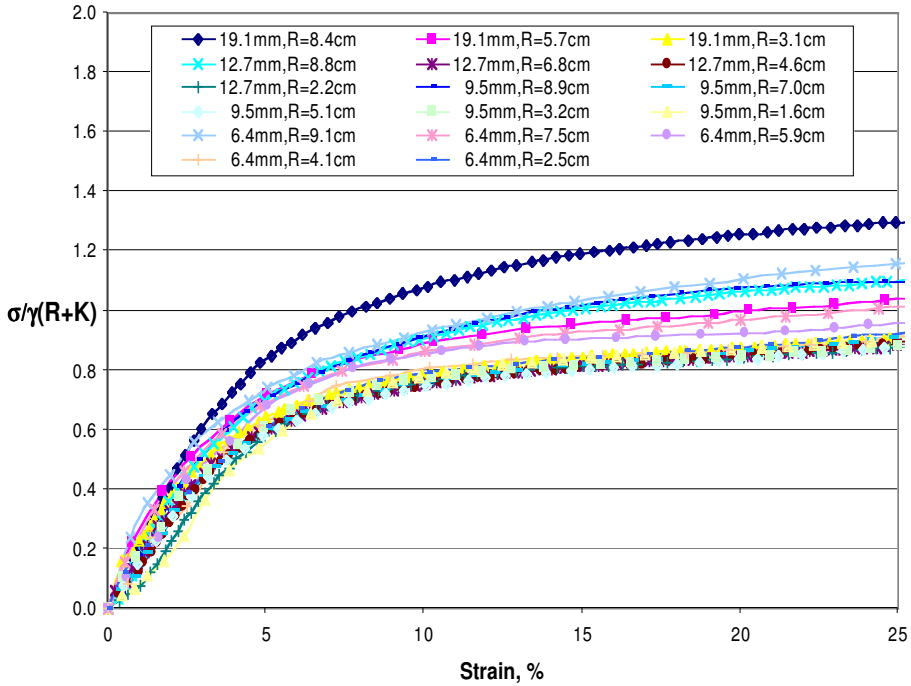
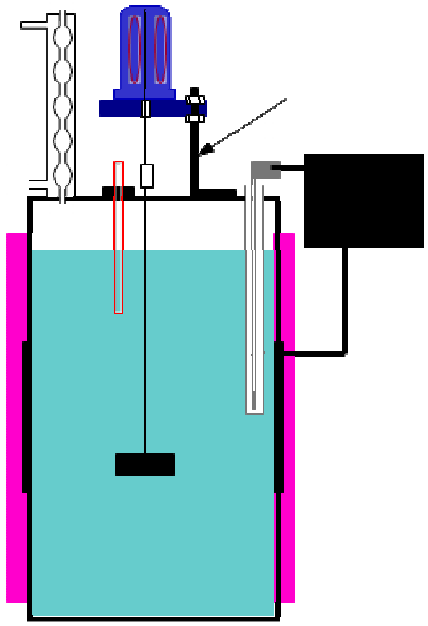
Modified Characteristic Strength



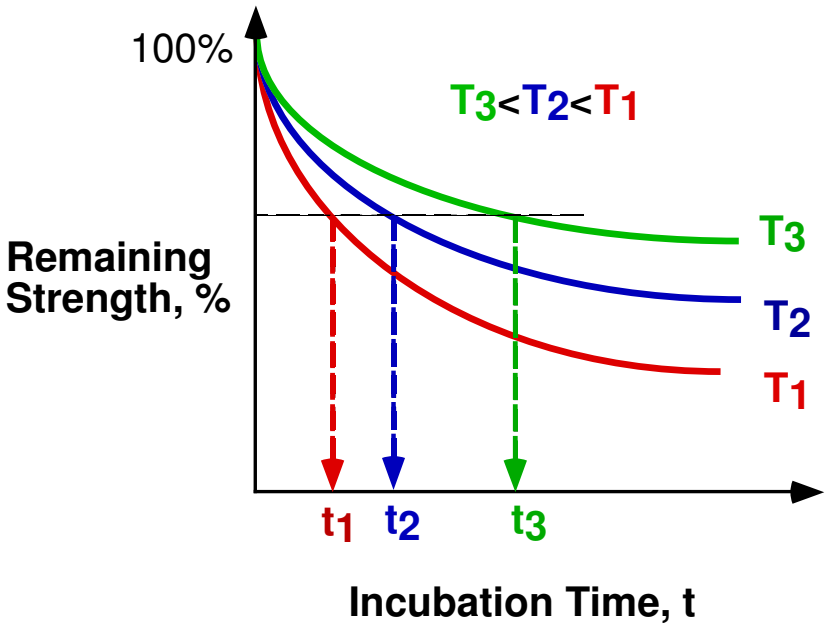


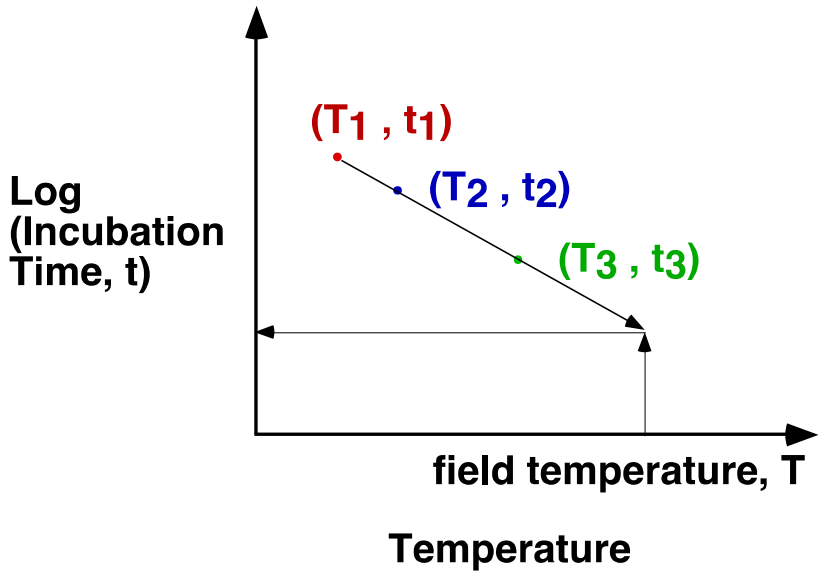
2. Durability in Aggressive Environments

- 12 month study
- 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

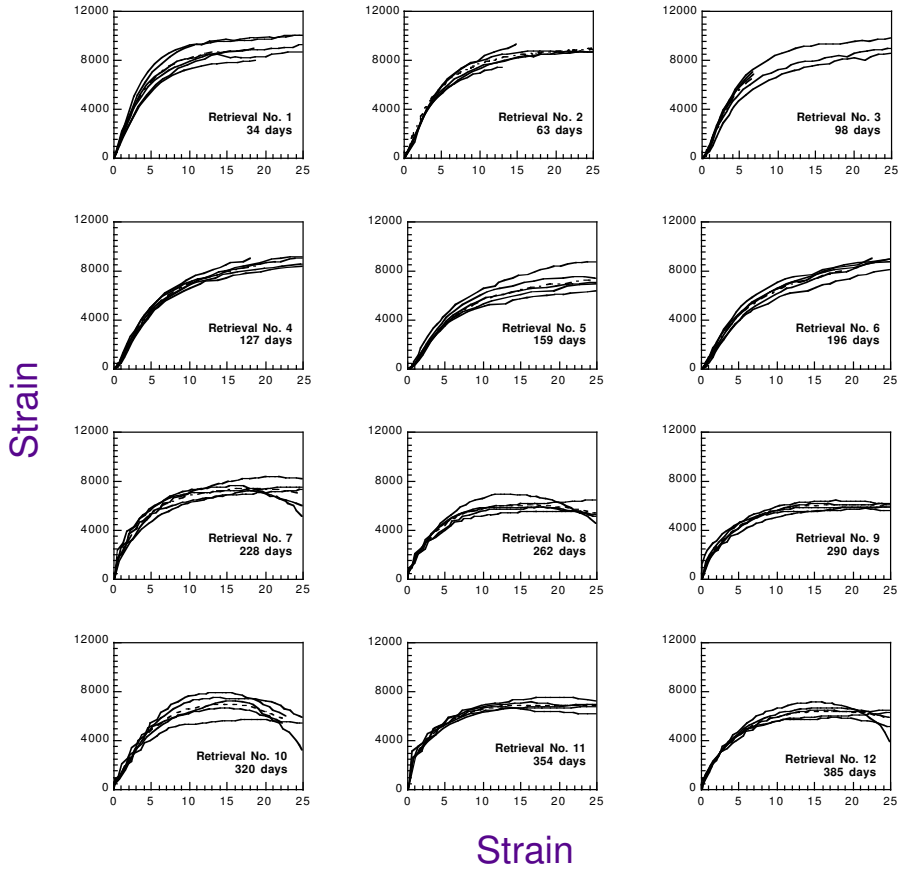




Results (Characteristic Strength v. Strain)

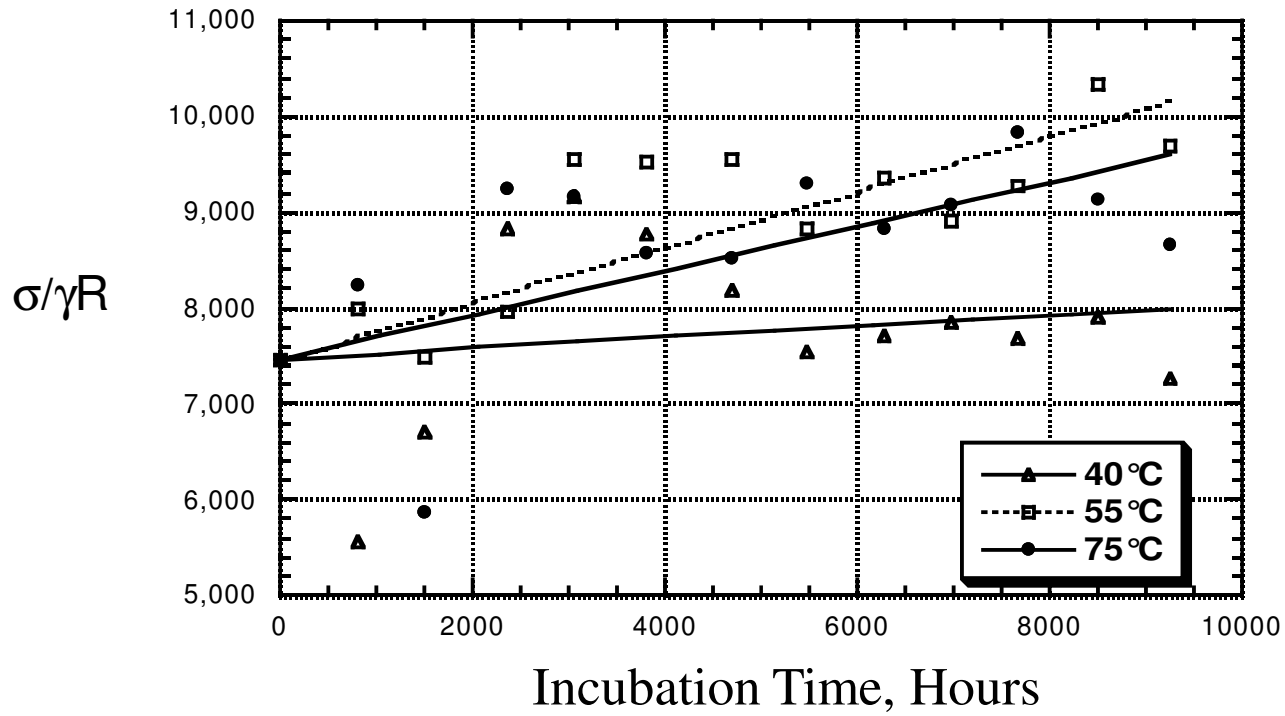
Limitations:

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



Specimens in Water

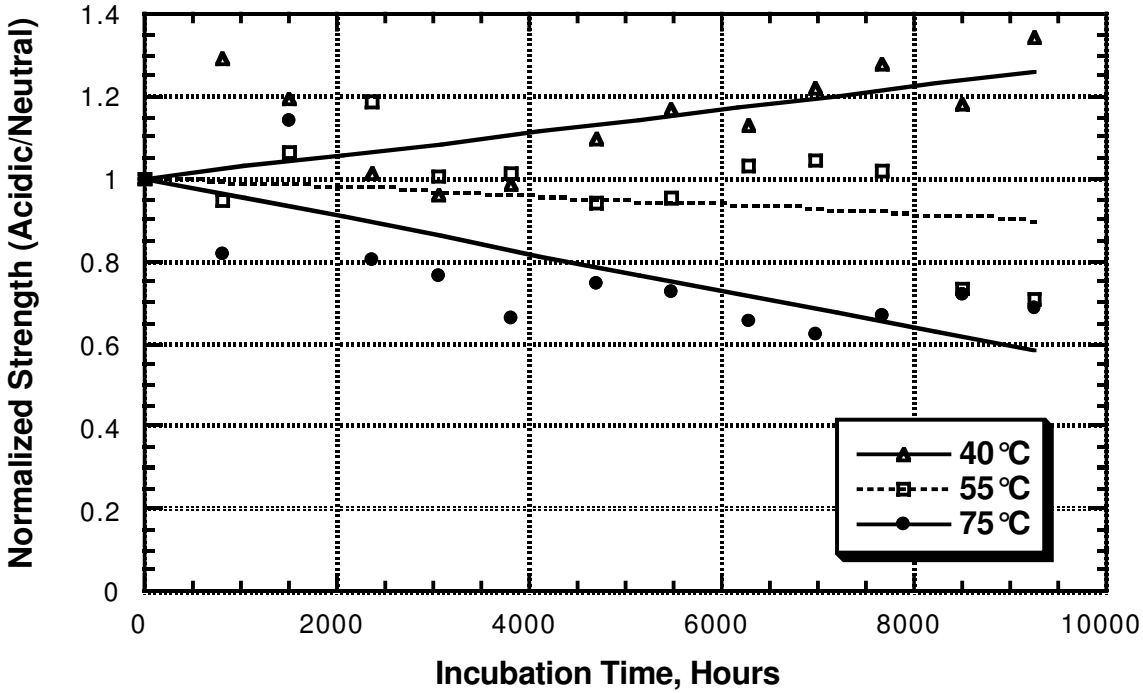
Increase in characteristic strength of specimens incubated in water!



@ 10% Strain

Specimens in Acid

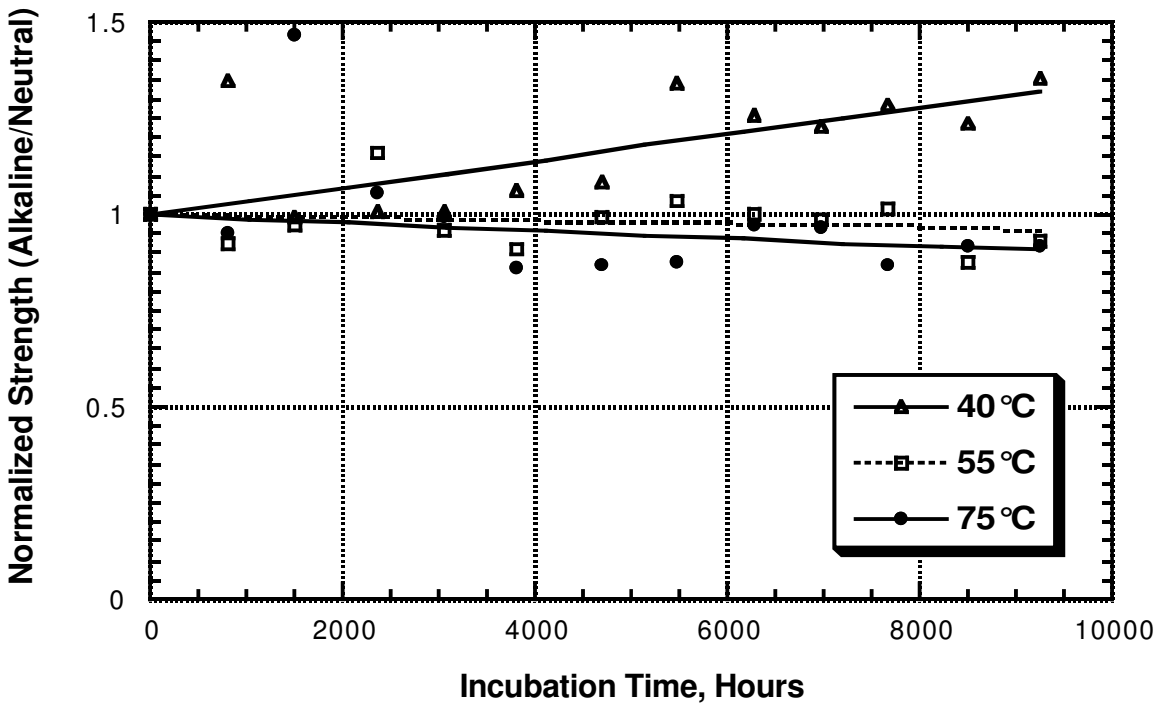
$$\frac{(\sigma/\gamma R) \text{ for pH } = 2}{(\sigma/\gamma R) \text{ for pH } = 7}$$



@ 10% Strain

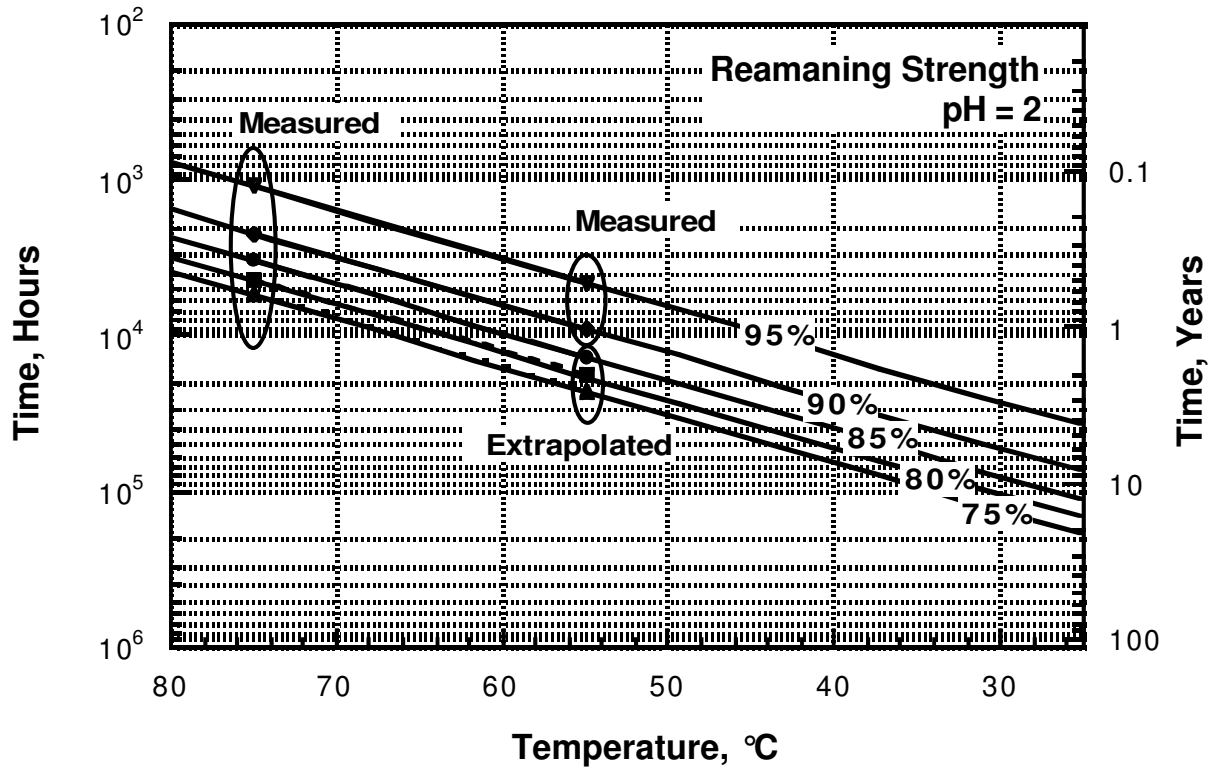
Specimens in Alkali

$$\frac{(\sigma/\gamma R) \text{ for pH } = 11}{(\sigma/\gamma R) \text{ for pH } = 7}$$



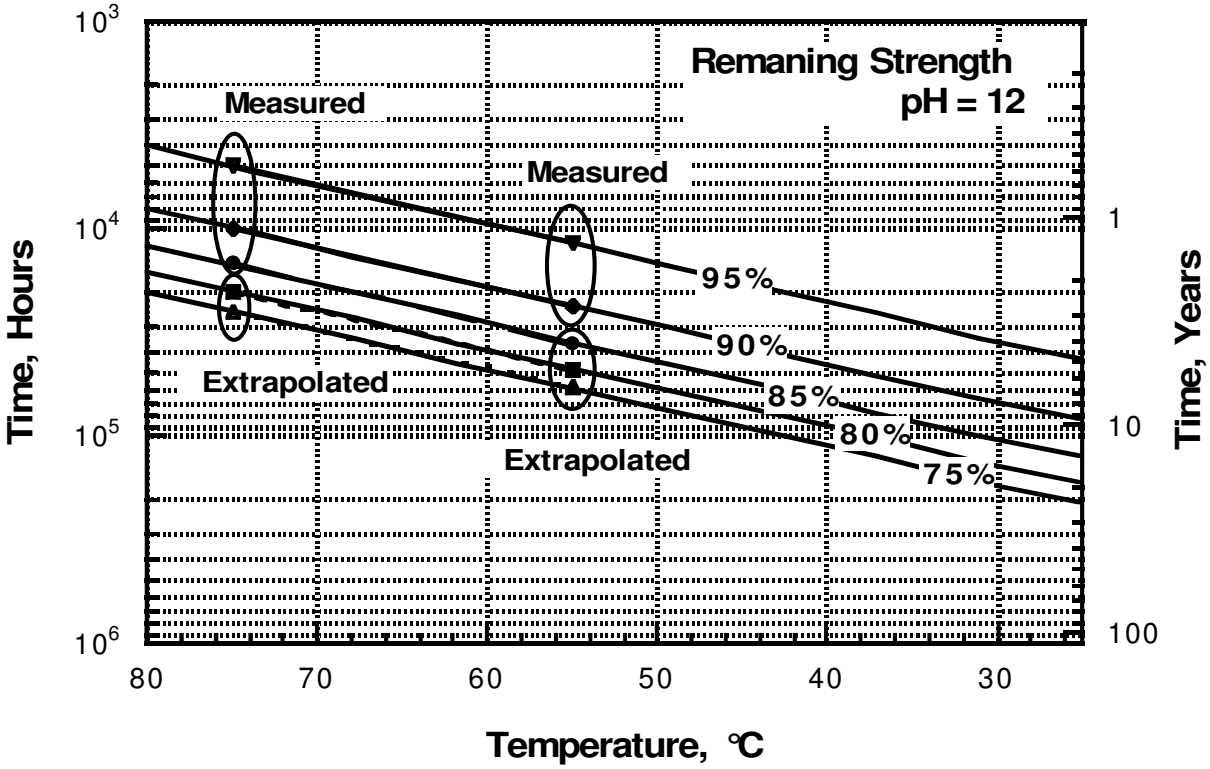
@ 10% Strain

Arrhenius Plot (Acidic)



Remaining Strength
@ 10% Strain

Arrhenius Plot (Alkali)



Remaining Strength
@ 10% Strain

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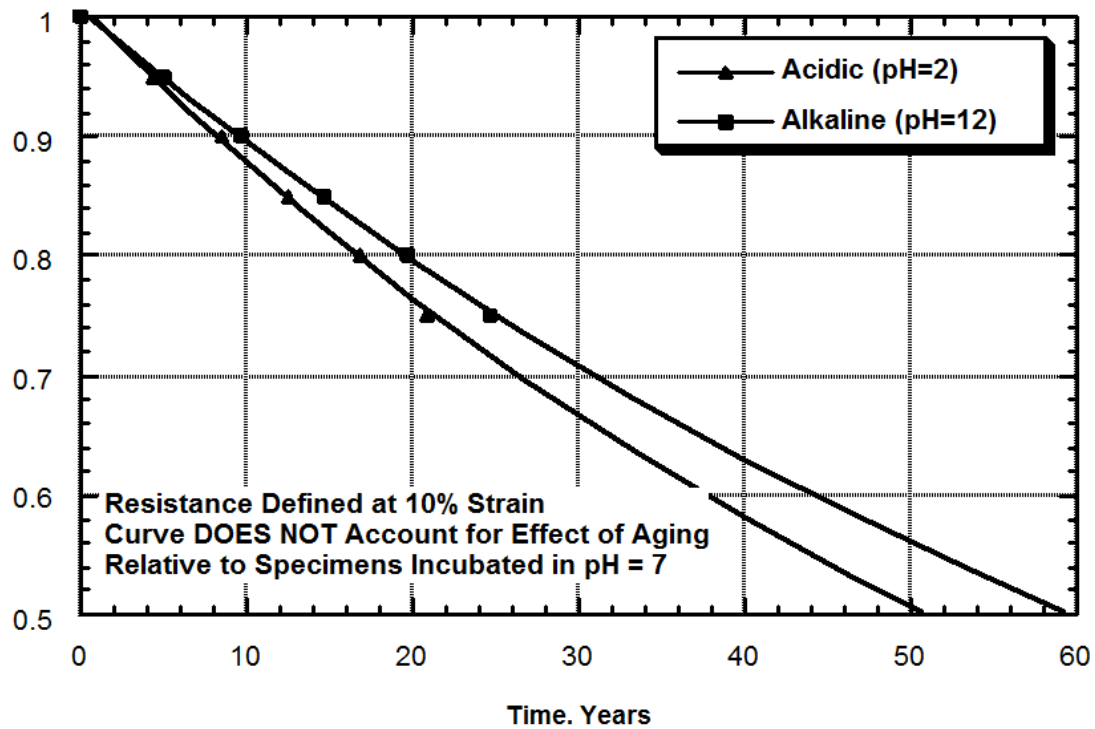
Performance at Field Temperature

Remaining Relative Strength @25° C



@ 10% Strain
Relative to specimens in water

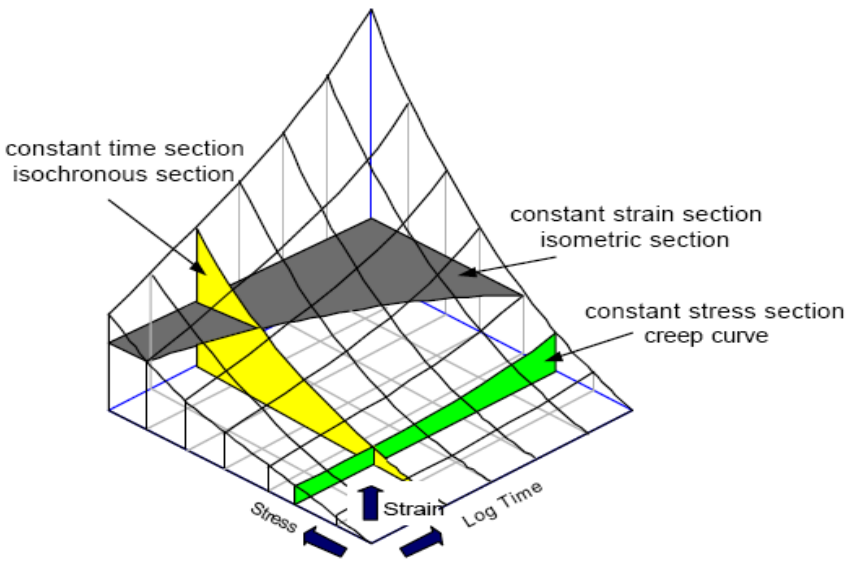
3. Creep Prediction Methods

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



Validation using virgin HDPE provides consistent properties & eliminates scatter due to material properties

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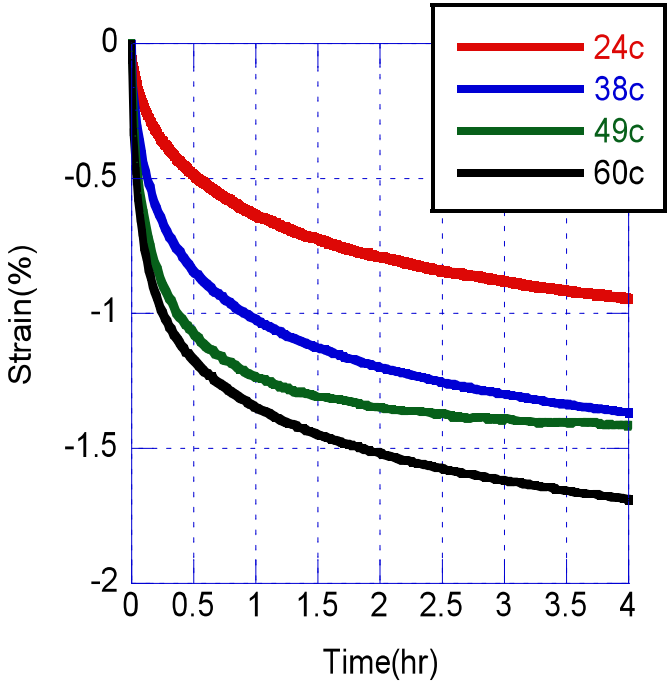
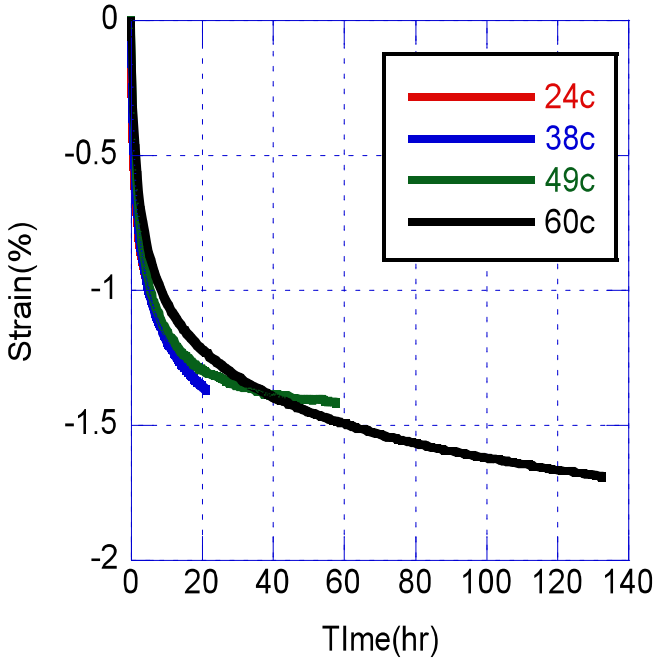
Time Temperature Superposition (TTS)
Virgin HDPE @ 800 psi





Temperature	24° C (72°F)	38°C (100°F)	49°C (120°F)	60°C (140°F)
a_T	1	5.26	14.15	33.12

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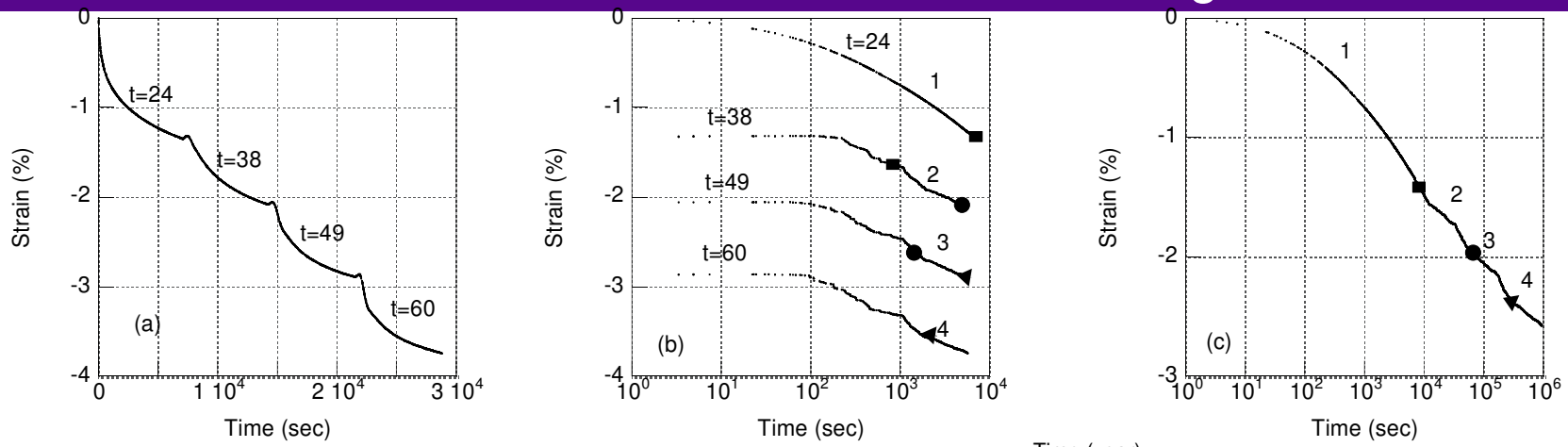
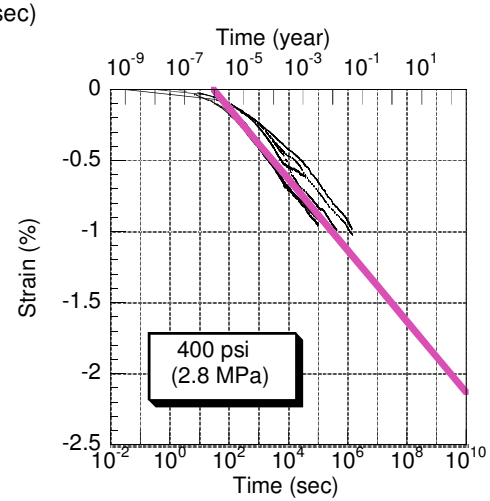
Stepped Isothermal Method (SIM)
Virgin HDPE @ 400 psi



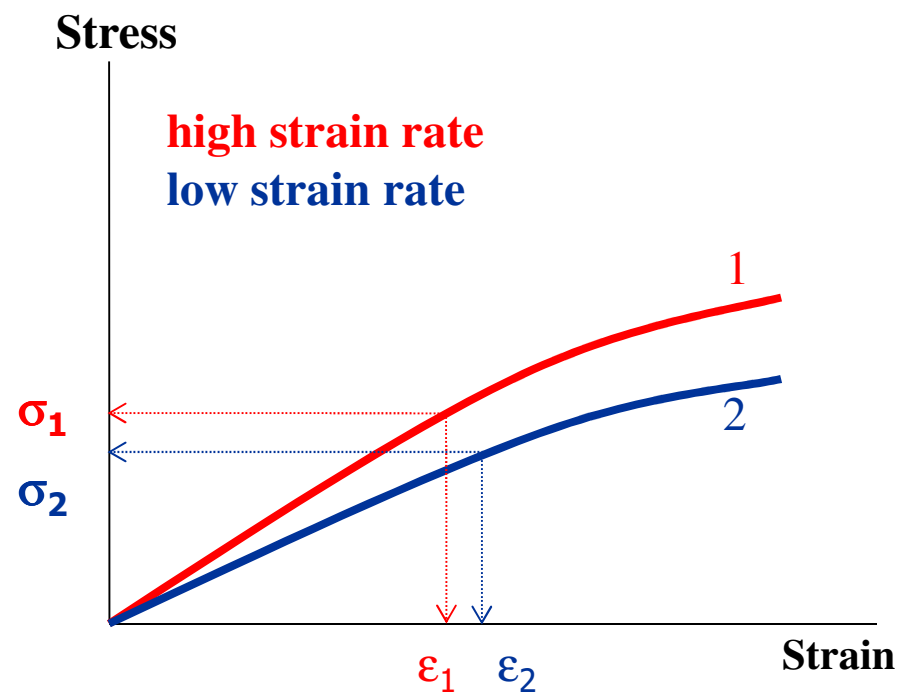
- Only one specimen is used
- Eliminates scatter due to specimen variability
- Results require a great deal of judgment and are highly user dependent



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 density= σε



$$\left(\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right)^m = \frac{\sigma_1}{\sigma_2} = \frac{\varepsilon_2}{\varepsilon_1}$$

$$\sigma_1\varepsilon_1 = \sigma_2\varepsilon_2$$

SED Method

$$\left(\frac{\dot{\varepsilon}_{r1}}{\dot{\varepsilon}_{r2}}\right)^m = \frac{\varepsilon_{r2}}{\varepsilon_{r1}}$$

$$\sigma_{r1} = E_{r1} \times \varepsilon_{r1} \Rightarrow \frac{\sigma_{r1}}{\varepsilon_{r1}} = E_{r1}$$

$$\sigma_{r2} = E_{r2} \times \varepsilon_{r2} \Rightarrow \frac{\sigma_{r2}}{\varepsilon_{r2}} = E_{r2}$$

$$\frac{E_{r1} \times \varepsilon_{r1}^2}{2} = \frac{E_{r2} \times \varepsilon_{r2}^2}{2} \quad \Rightarrow \left(\frac{\varepsilon_{r2}}{\varepsilon_{r1}}\right)^2 = \frac{E_{r1}}{E_{r2}} \quad \Rightarrow \quad \frac{\varepsilon_{r2}}{\varepsilon_{r1}} = \sqrt{\frac{E_{r1}}{E_{r2}}}$$

$$\left(\frac{\dot{\varepsilon}_{r1}}{\dot{\varepsilon}_{r2}}\right)^m = \sqrt{\frac{E_{r1}}{E_{r2}}} \quad \Rightarrow \quad m = \frac{\log\left(E_{r1}/E_{r2}\right)}{2\log\left(\dot{\varepsilon}_{r1}/\dot{\varepsilon}_{r2}\right)}$$

$$SED_{ci} = \frac{\sigma_c \times \varepsilon_i}{2}$$

$$\left(\frac{\dot{\varepsilon}_r}{\dot{\varepsilon}_i}\right)^m = \frac{\varepsilon_i}{\varepsilon_r} = \frac{\dot{\varepsilon}_i \times t_i}{\dot{\varepsilon}_r \times t_r}$$

$$SED_{ci} = \frac{E_r \times \varepsilon_r^2}{2} \Rightarrow \frac{E_r \times \dot{\varepsilon}_r^{\,2} \times t_r^{\,2}}{2}$$

$$SED_{ci} = \frac{\sigma_c \times \varepsilon_i}{2} = \frac{\sigma_c \times \dot{\varepsilon}_i \times t_i}{2}$$

$$\sigma_c \times \dot{\varepsilon}_i \times t_i = E_r \times \dot{\varepsilon}_r^{\,2} \times t_r^{\,2}$$

$$\dot{\varepsilon}_i = \sqrt[2m+1]{\frac{\sigma_c \times \dot{\varepsilon}_r^{\,2m}}{E_r \times t_i}}$$

$$t_r = \sqrt{\frac{\sigma_c \times \dot{\varepsilon}_i \times t_i}{E_r \times t_r}}$$

$$\varepsilon_i = \dot{\varepsilon}_i \times t_i$$

$$\varepsilon_c = \varepsilon_i / 2$$

$$\left(\frac{\dot{\varepsilon}_r}{\dot{\varepsilon}_i}\right)^m = \frac{\varepsilon_i}{\varepsilon_r} = \frac{\dot{\varepsilon}_i \times t_i}{\varepsilon_r}$$

$$\sigma_c \times \dot{\varepsilon}_i \times t_i = E_r \times \dot{\varepsilon}_r^{\,2} \times t_r^{\,2} = E_r \times \varepsilon_r^{\,2}$$

$$t_i = \sqrt[m]{\frac{\varepsilon_r^{\,2m+1} \times E_r^{\,m+1}}{\sigma_c^{\,m+1} \times \dot{\varepsilon}_r^{\,m}}}$$

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.
- Creep is assumed to be as a very low strain rate process.
- The stress strain behavior of any material can be extrapolated for any strain rate.

$$\left(\frac{\dot{\varepsilon}_{r1}}{\dot{\varepsilon}_{r2}}\right)^{m} = \frac{\varepsilon_{r2}}{\varepsilon_{r1}} \quad (1)$$

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

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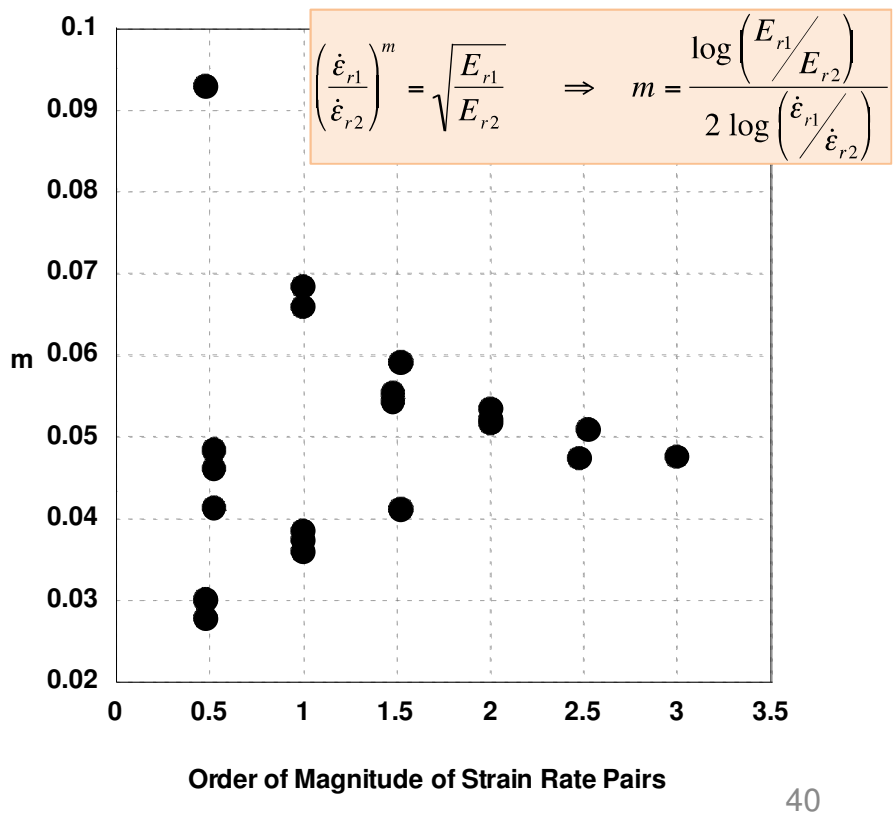
Variation of *m* with Respect to the Order of Magnitude in Reference Strain Rates for Virgin HDPE

- m can be computed for any pair of strain rates
- m converge to a unique number as the order of magnitude of strain rates between different pairs increases.



SED Method… cont.

- A creep stress, σ_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 the *imaginary equivilant-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, εi, can be calculated from the strain rate, using Eq. 4.
- Creep strain is taken as half of εi, (Eq. 5) to account for the fact that creep stress is constant but in iECSS the stress varies

$$\dot{\varepsilon}_i = \sqrt[2m+1]{\frac{\sigma_c \times \dot{\varepsilon}_r^{\,2m}}{E_r \times t_i}} \quad (3)$$

$$\varepsilon_i = \dot{\varepsilon}_i \times t_i \quad (4)$$

$$\varepsilon_c = \varepsilon_i / 2 \quad (5)$$

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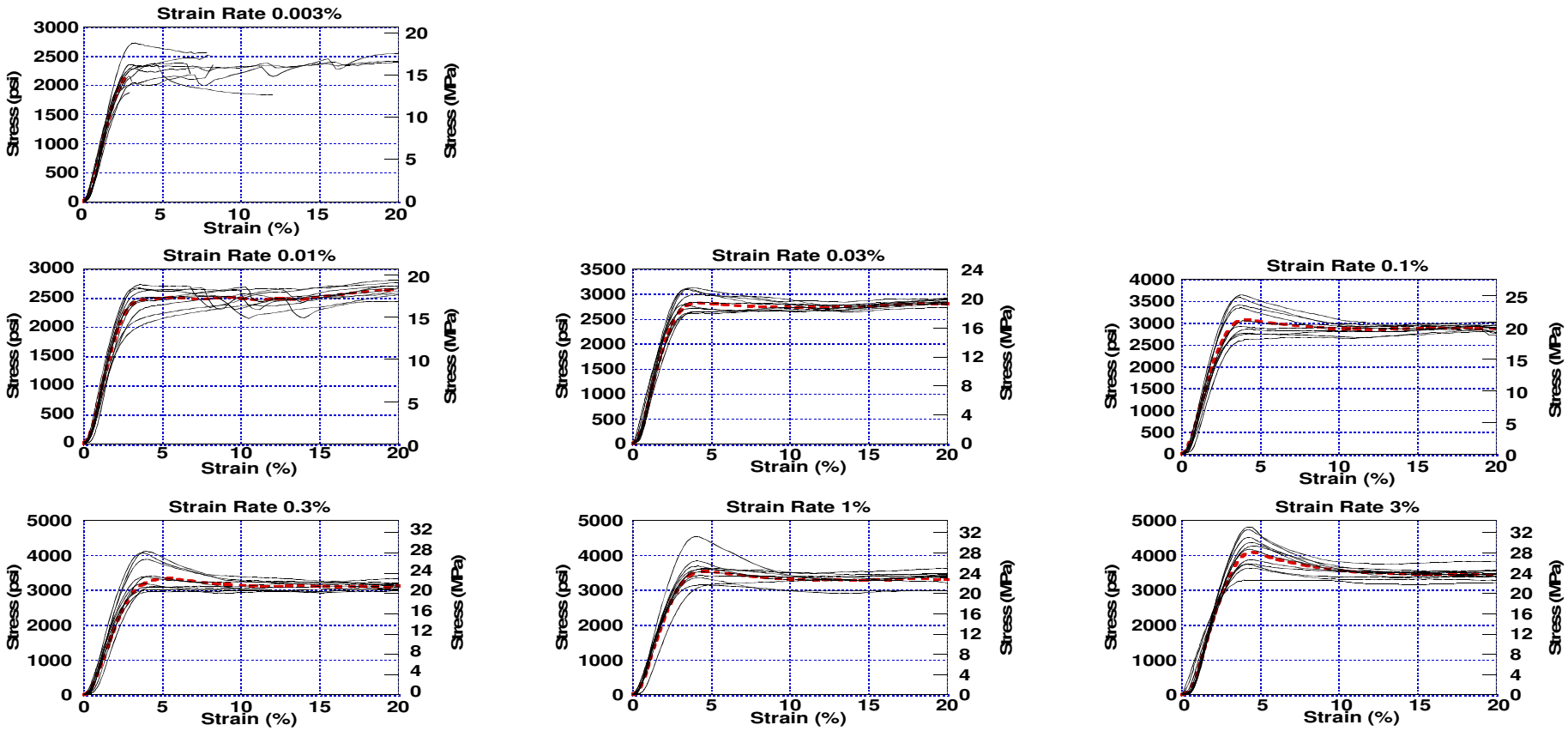
Stress-Strain on Recycled HDPE



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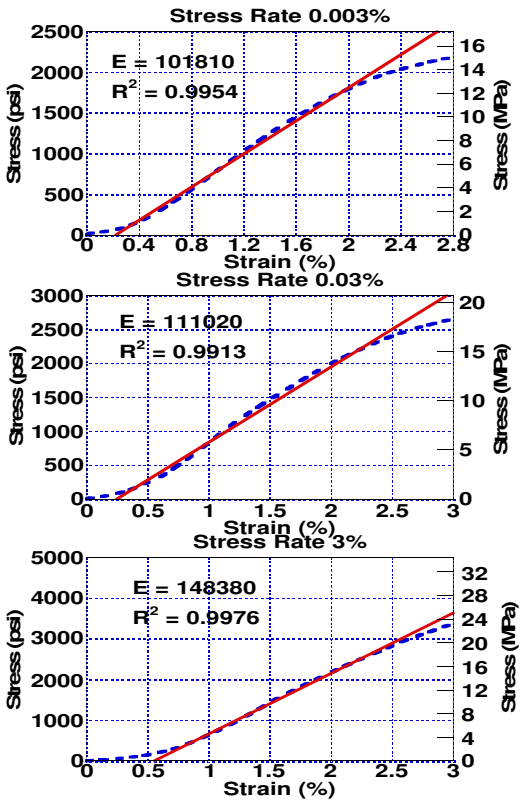
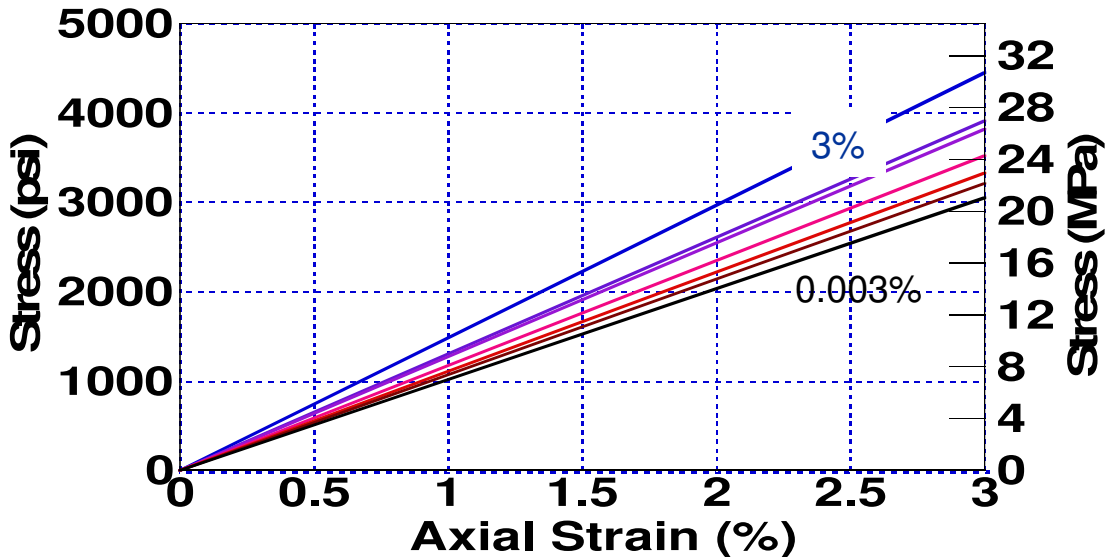
Obtain Modulus of Elasticity for Each Rate of Loading





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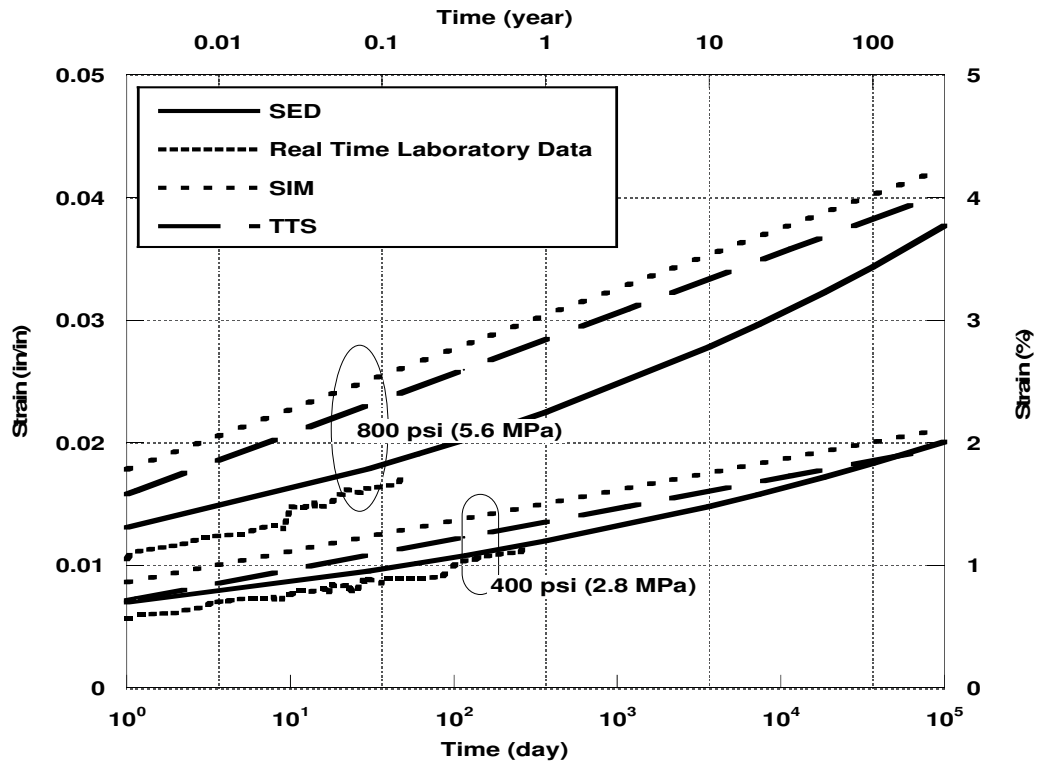
Comparing SED, SIM, & TTS for Virgin HDPE

TTS: Polymer changes due to incubation temperature limits acceleration to a factor of 30.

SIM: Method is user dependent.

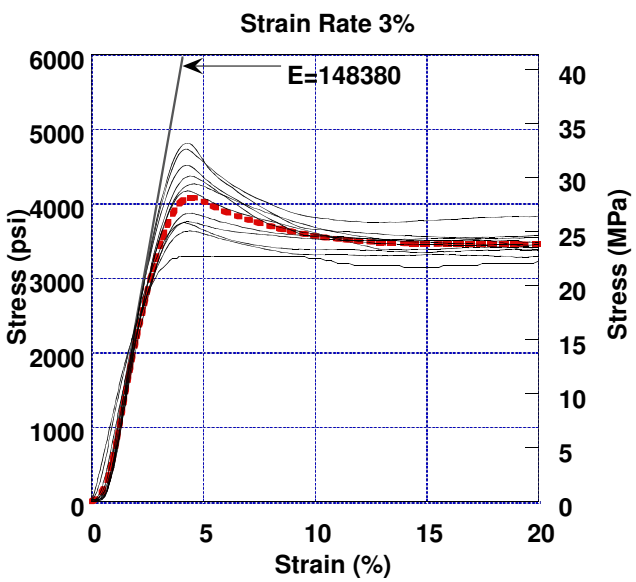
SED: Holds most promise.



Stress- Strain on Recycled HDPE

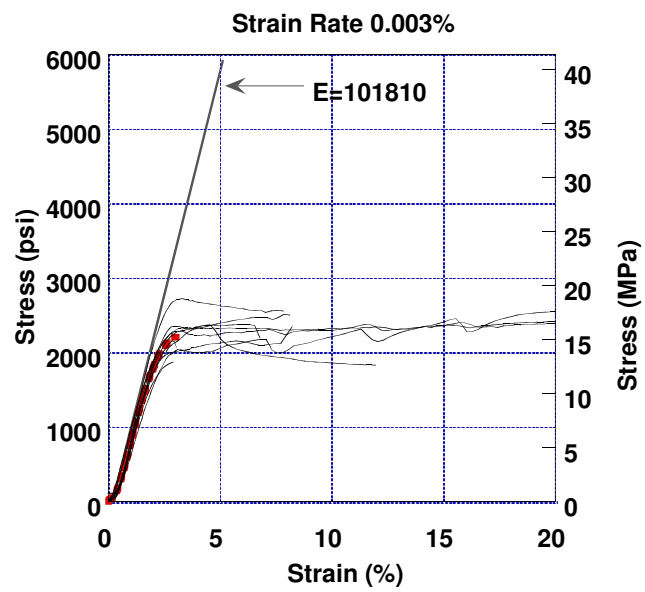
Strain Rate = 3%

E= 148,380 psi

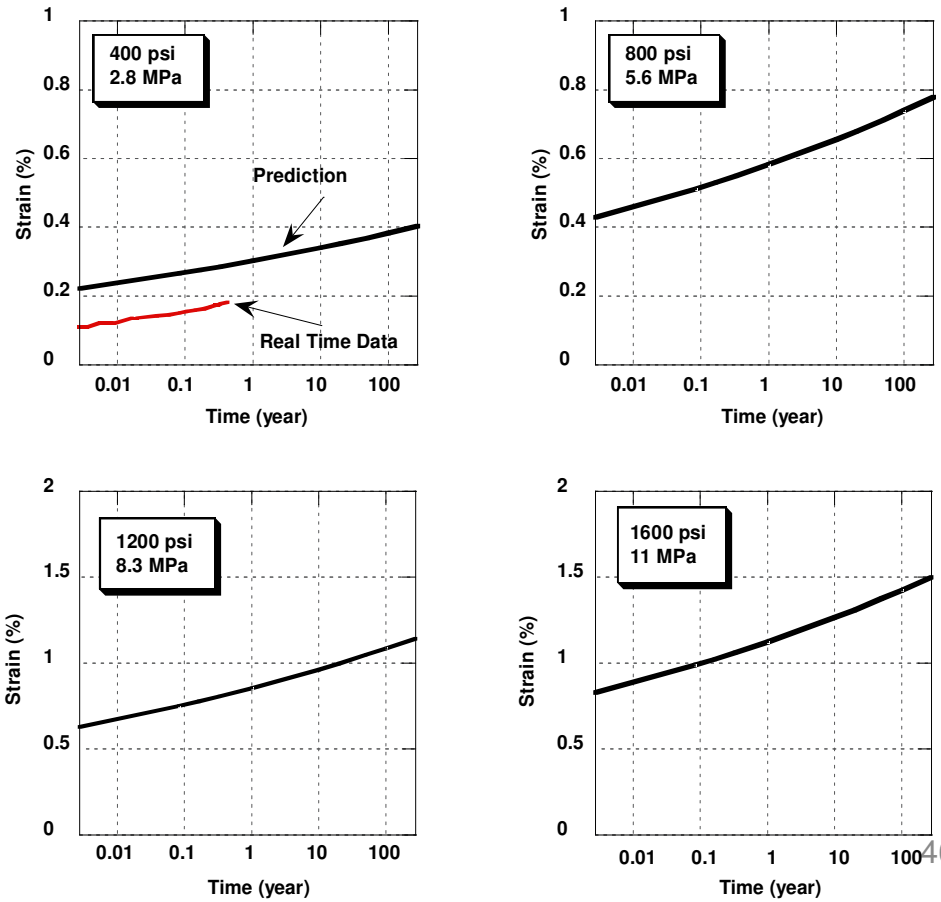


Strain Rate = 0.003%

E= 101,810 psi



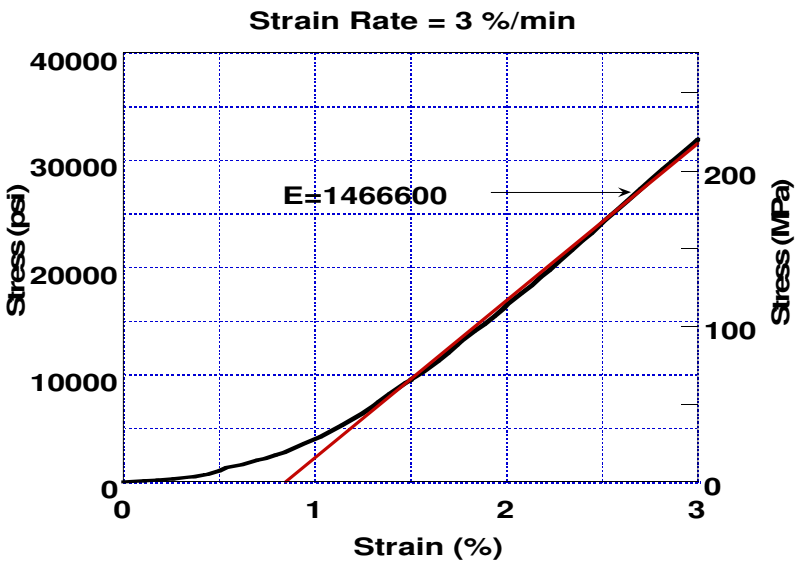
Predicted Creep of Recycled HDPE

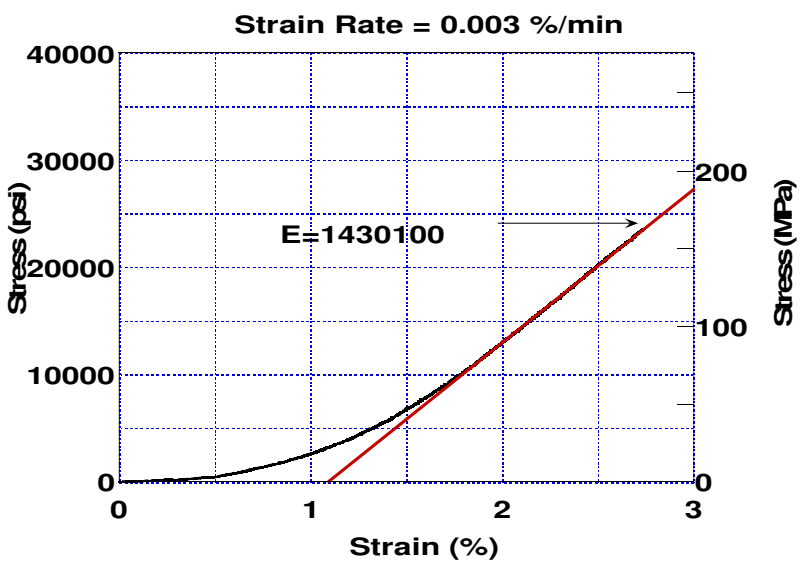


Using SED

Predicted using pairs having a difference in order of magnitude > 2

Stress Strain of E-Glass

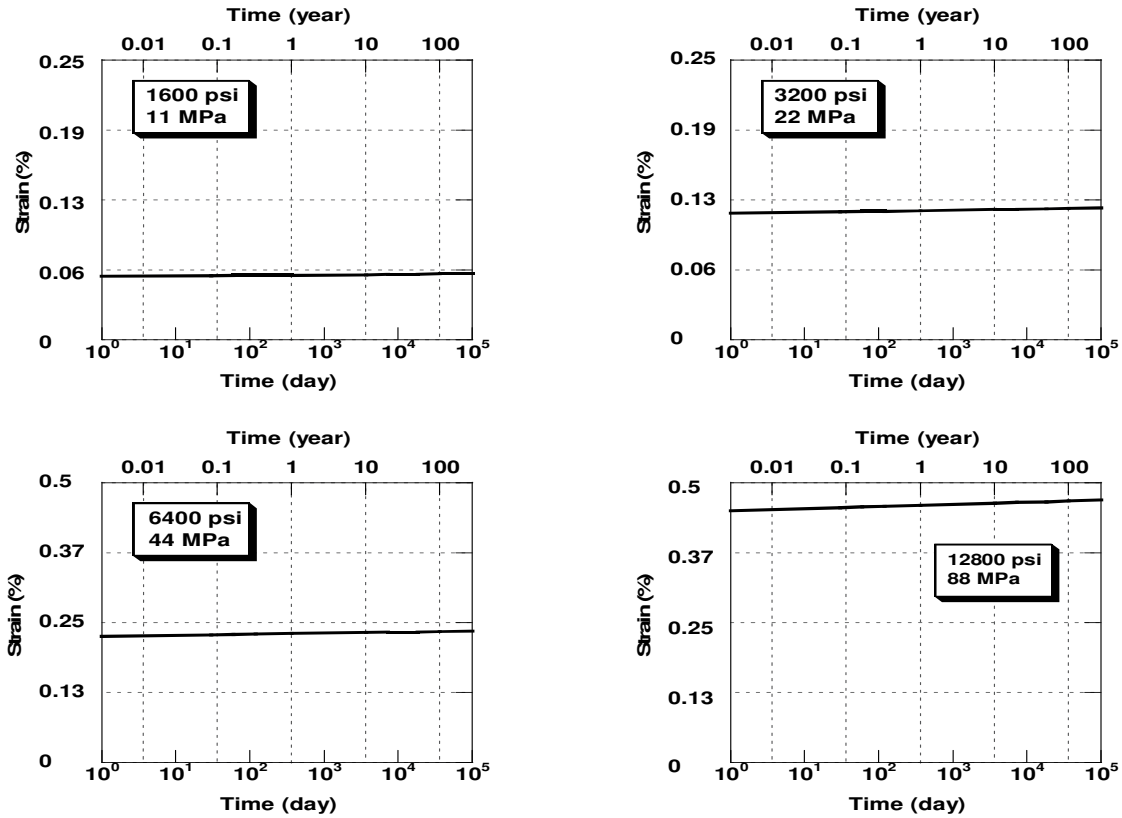




Predicted Creep of FRP

Using SED

Predicted using pairs having a difference in order of magnitude > 2



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Composite Modulus of Elasticity (psi)

		Modulus of Elasticity (3%/min)	Modulus of Elasticity (0.003 %/min)
	E-Glass	1,466,600	1,430,100
	Recycled HDPE	148,380	101,810
E-Glass (%)	3%	187,927	141,659
Recycled HDPE (%)	97%		
E-Glass (%)	8%	253,838	208,073
Recycled HDPE (%)	92%		

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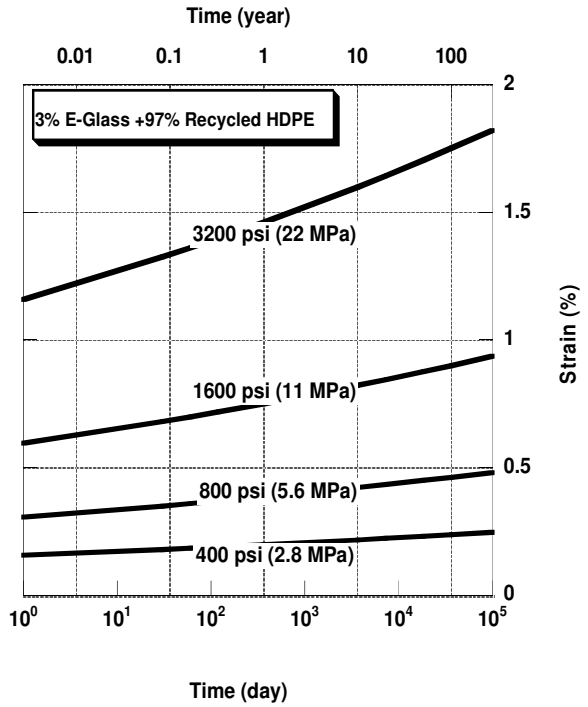
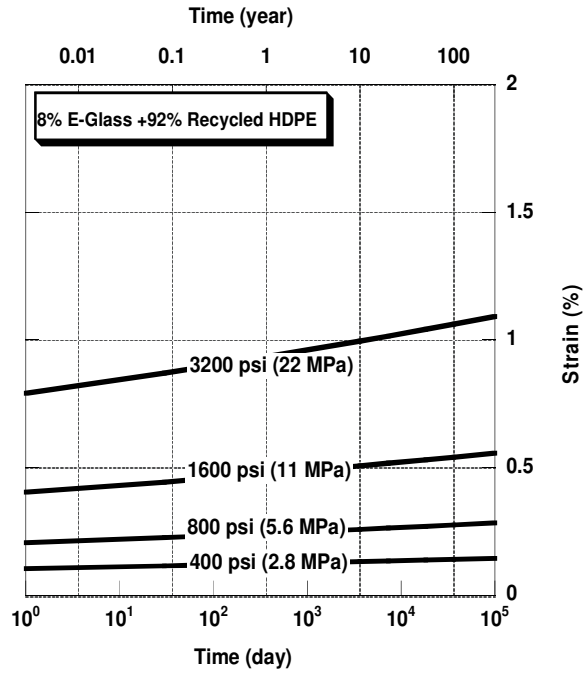
Predicted Creep of Reinforced Polymeric Piling



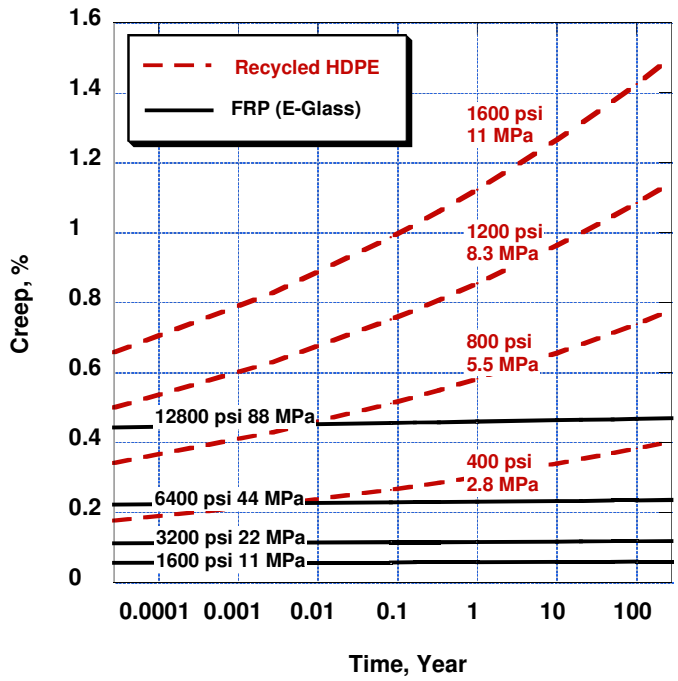
3% FRP &
97% Recycled HDPE

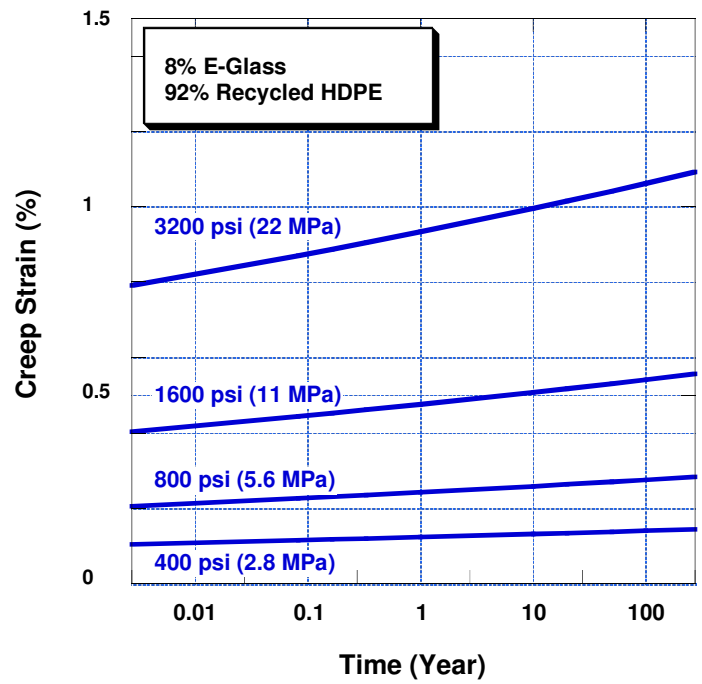


8% FRP &
92% Recycled HDPE

3. Creep Behavior

SED predicts that creep of typical RPP piles under typical loads is within an acceptable range for civil engineering applications





Conclusions

RPP creeps by 0.5-0.8% in 100 years when typical RPP geometries and reinforcement ratios are considered.

- Recycled-HDPE will creep by 1.1% in 100 years when loaded at an ultimate stress of 1,200 psi (8.3 MPa).
- FRP loaded in compression will creep by less than 0.5% in 100 years when loaded at an ultimate stress of 128,000 psi (88 MPa).

SED is suitable for

- Comparing the creep behavior of different polymeric products for preliminary design.
- QA/QC of polymeric materials which vary by manufacturer and by production season, depending on the constituents of the waste stream

Limitations, Assumptions, & Precautions

- Strain compatibility of HDPE & FRP is valid in the long term
  - Difference in the creep rates of FRP and HDPE may affect the composite modulus used for SED computations.
- Methodology is limited to small strains
- Effect of foaming which reduce the computed modulii was neglected
  - Foaming increasing the predicted creep
  - Foaming over-emphasizes the role of FRP
  - These 2 effects may negate each other
- Temperature is assumed constant
  - Piles with long above ground stick-ups may be subject to wide temperature fluctuation.

Geotechnical Design

Interface Friction

Fiberglass

$\delta_{Fiberglass}$ = 60-90 % of $\delta_{Concrete}$
(Pando et al, 2002)

$\delta_{Fiberglass} \geq$ (10%) δ_{Steel}

(Frost Han, 1999)

HDPE

- δ = 8-15° (Geosynthetic Liners)
- Partial slippage along pile shaft during loading?

Bearing Capacity

- No foreseeable difference

Soil Structure Interaction

- Low Stiffness
  - Differential settlement in bearing
  - Advantageous in fendering
- Modulus is Load & Time Dependent
  - Time dependent load shedding?
  - Effect of creep on load transfer?

Structural Behavior

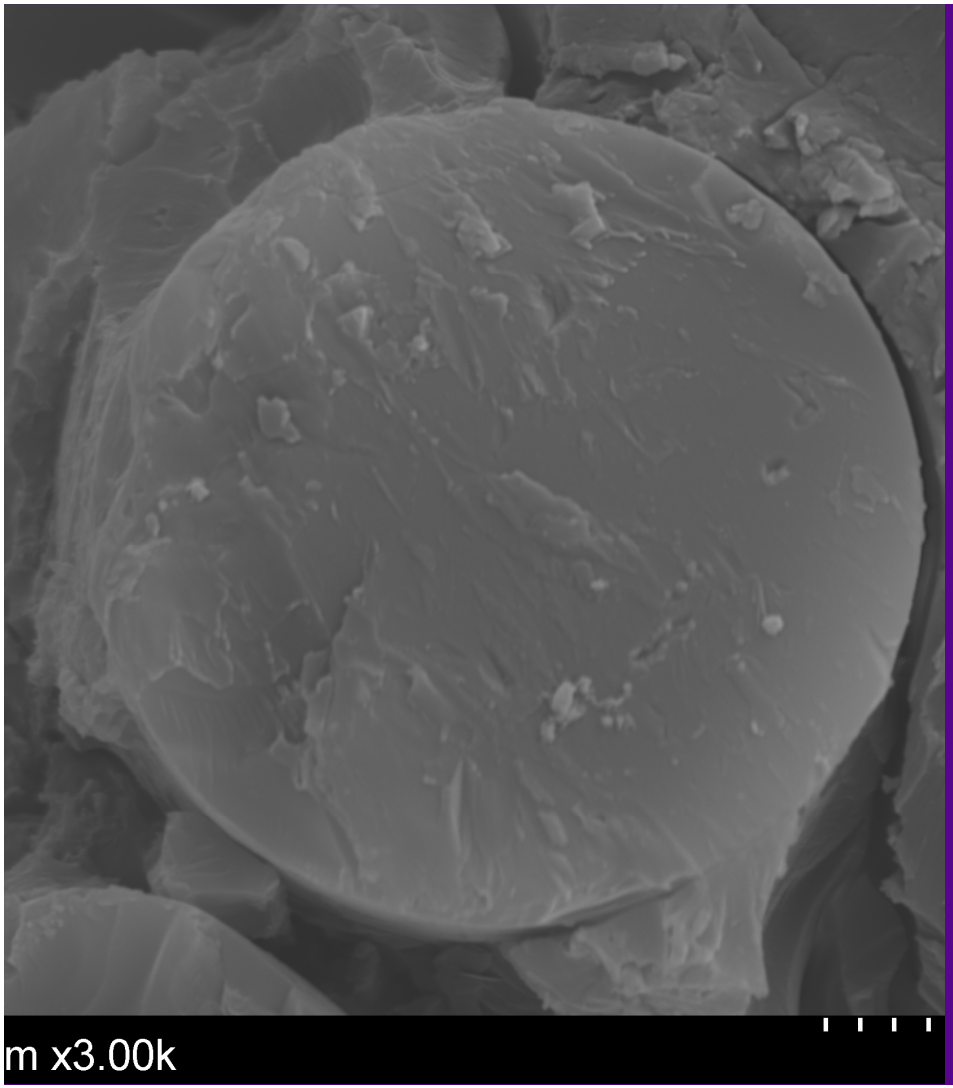
Low Stiffness

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

Variation in Properties $\Rightarrow$ FOS?

- Unit weight
- strength

Viscoelastic Creep



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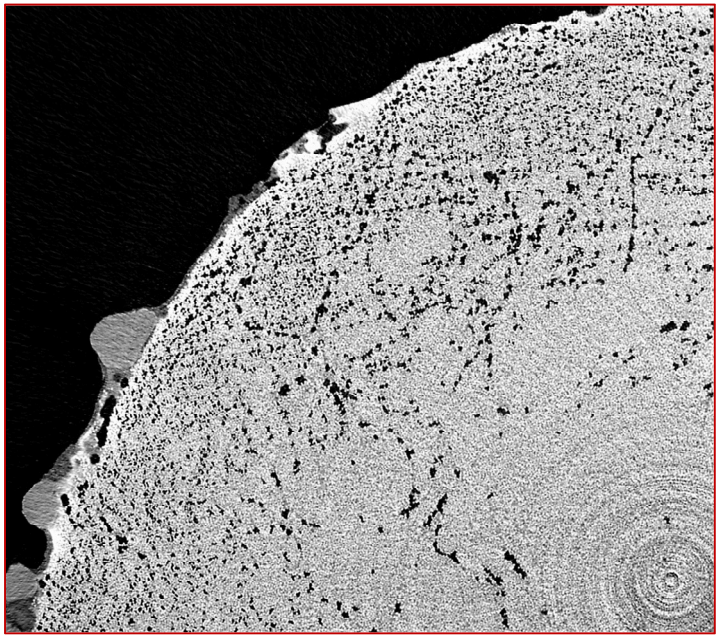
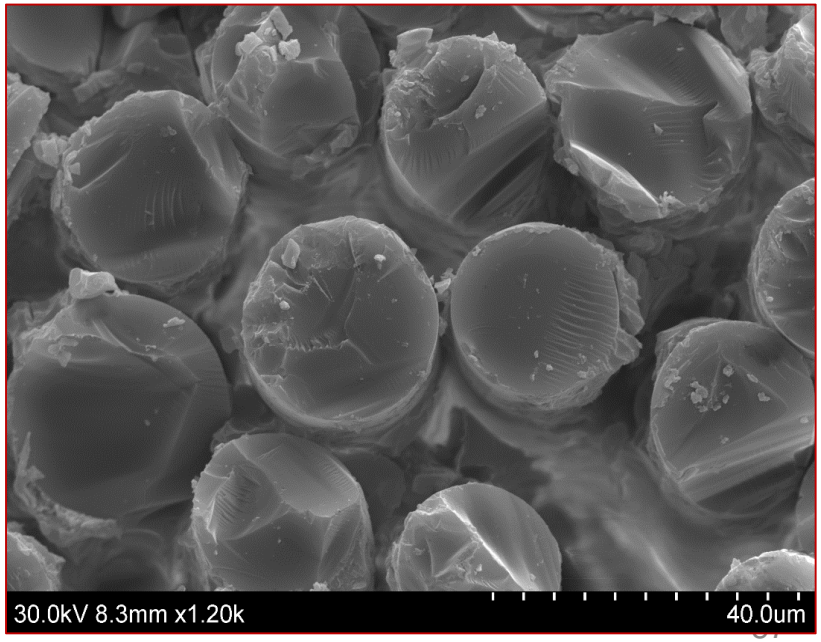
Recent Work: Failure Mechanism of FRP

As Received Cross Section Images

Porosity at the circumference of individual bars



Excellent bonding between fibers and matrix for #5 rebar



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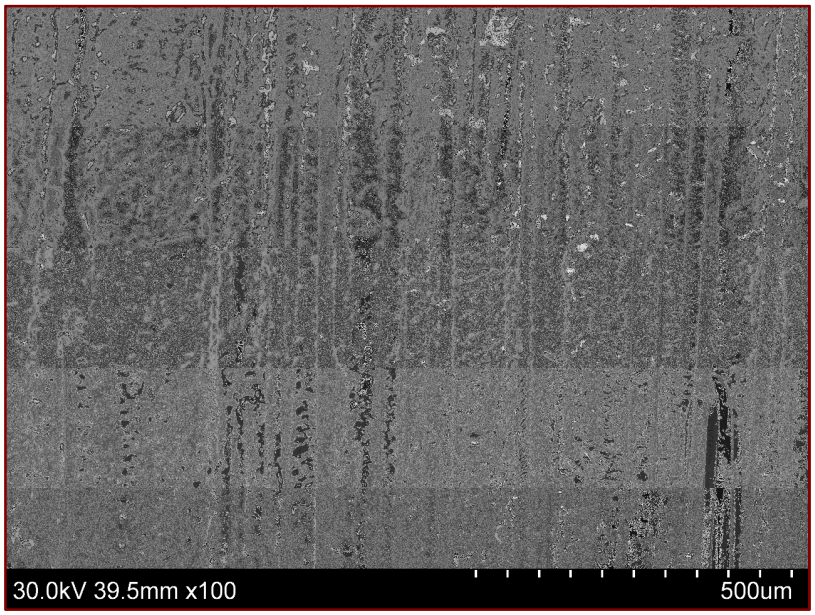
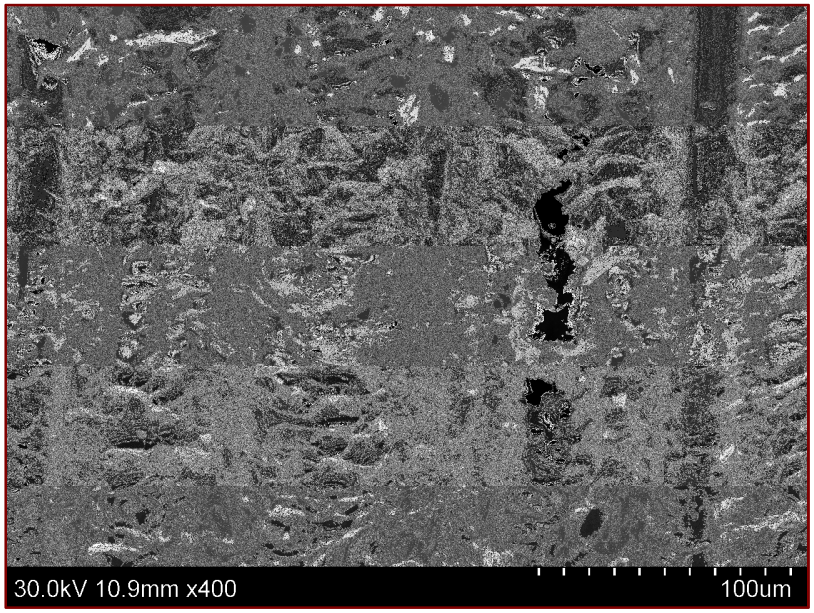
As Received Longitudinal Sections shows good bonding





Images of Nitrogen-Split #4 bars at 100x and 400x magnifications, showing good bonding between matrix and fibers

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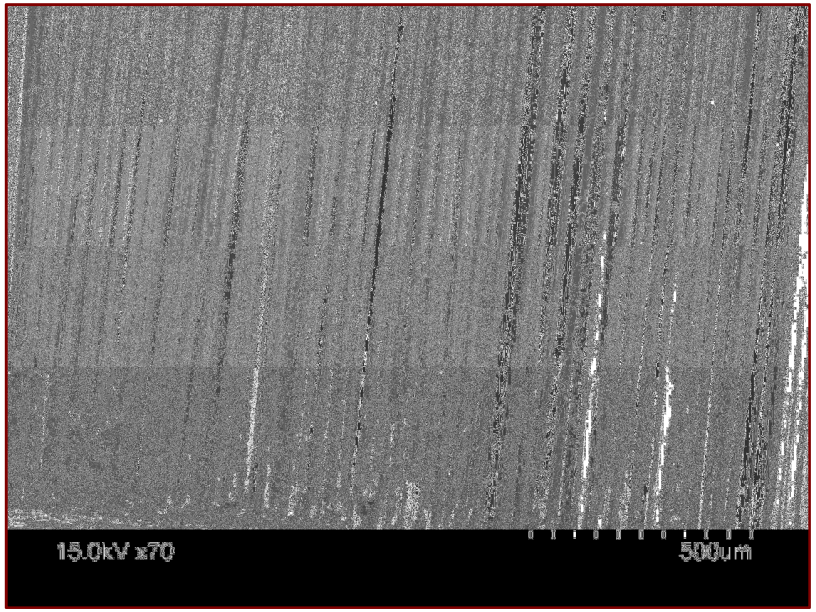
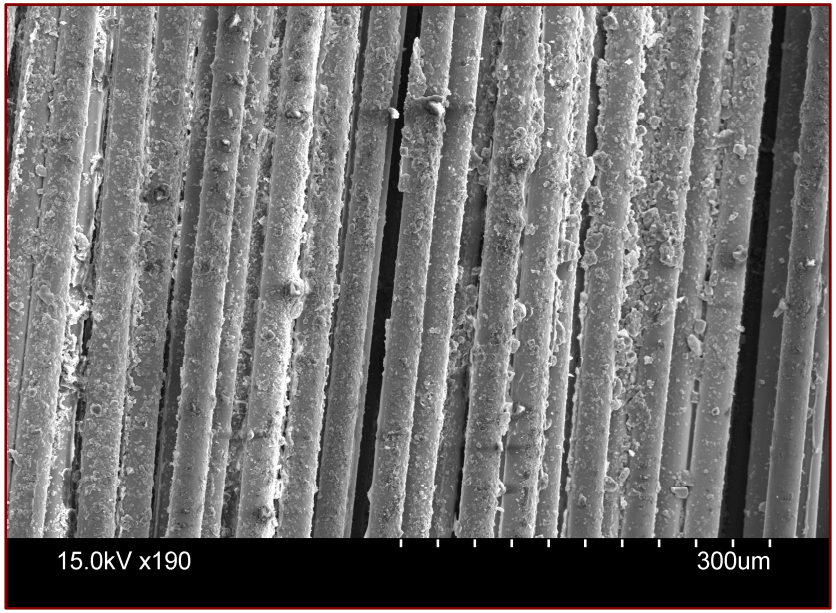
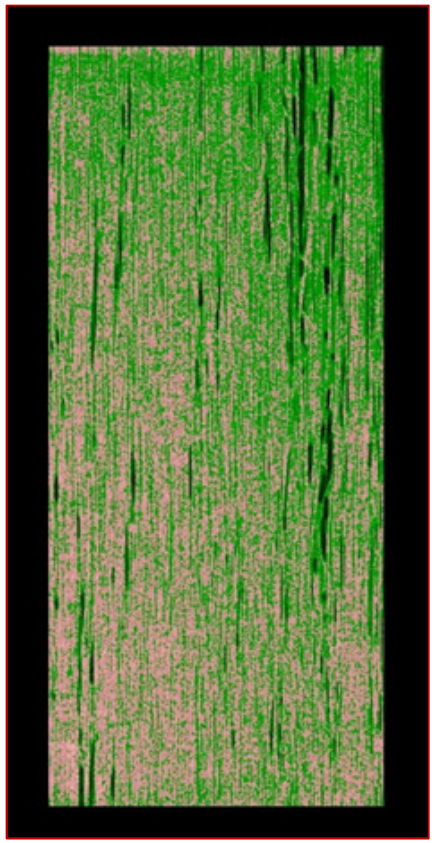
Burn-off test of as received specimens shows good fiber alignment

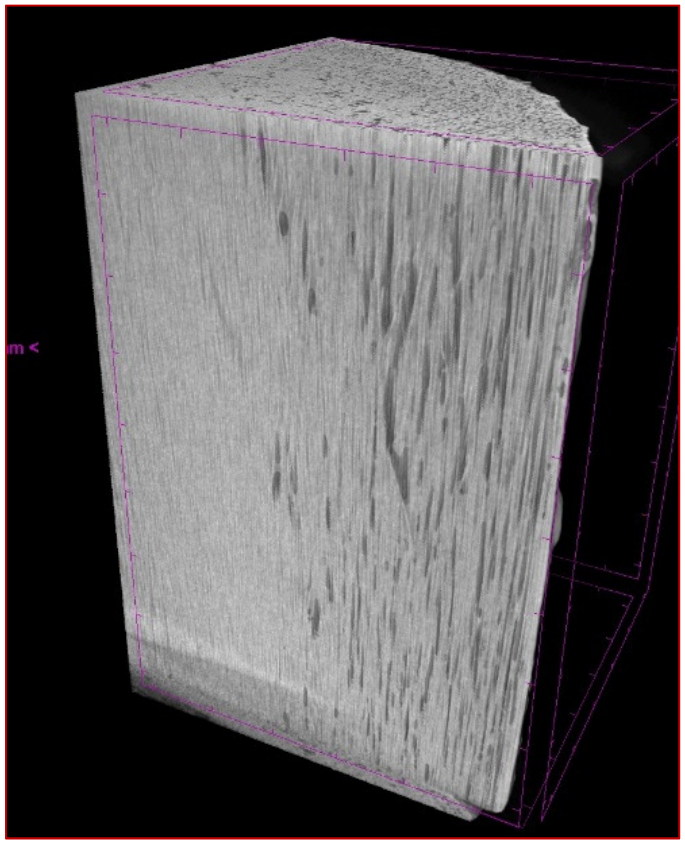




CT-scan images of as Received FRP Rebar

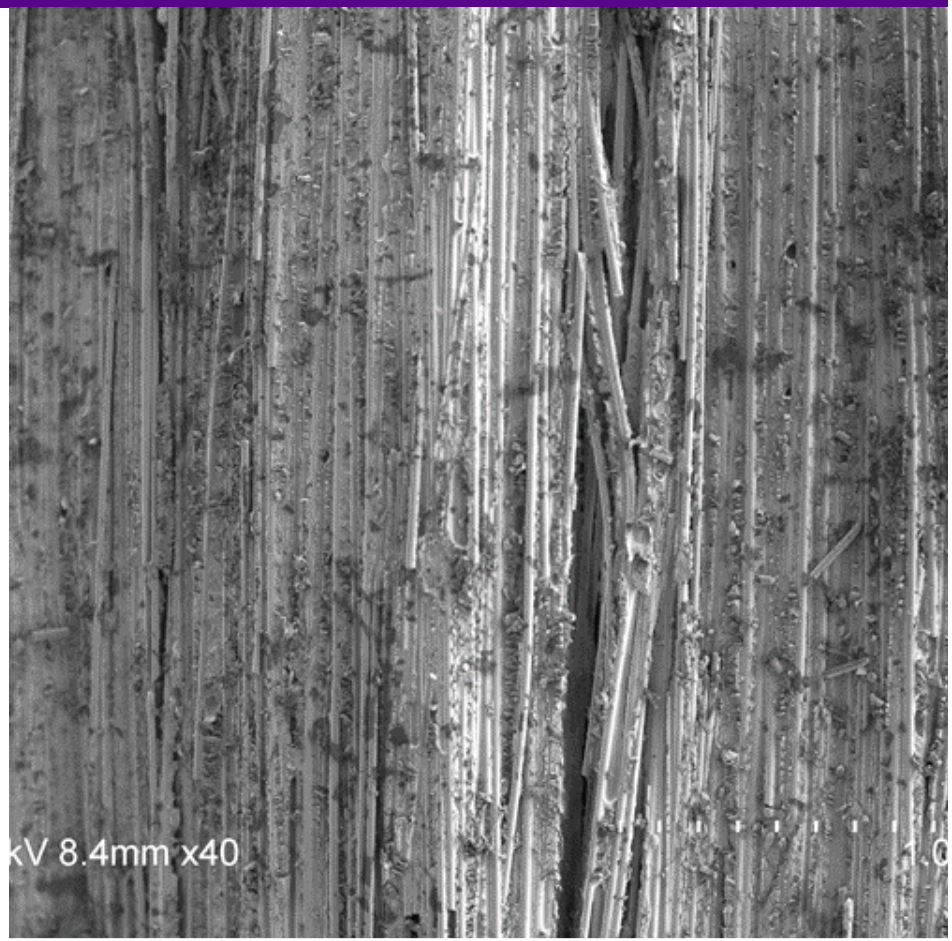
- **As received CT-scan images #5 rebar:**
  - LHS: Green Fibers, Black porosity
  - RHS: Specimen analyzed.
  - Volume Fraction ~ 60% fiber, 33% matrix, 7% void/porosity



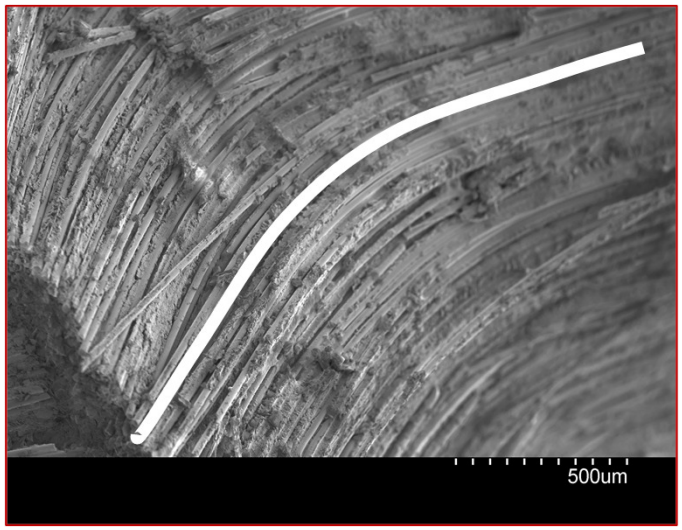


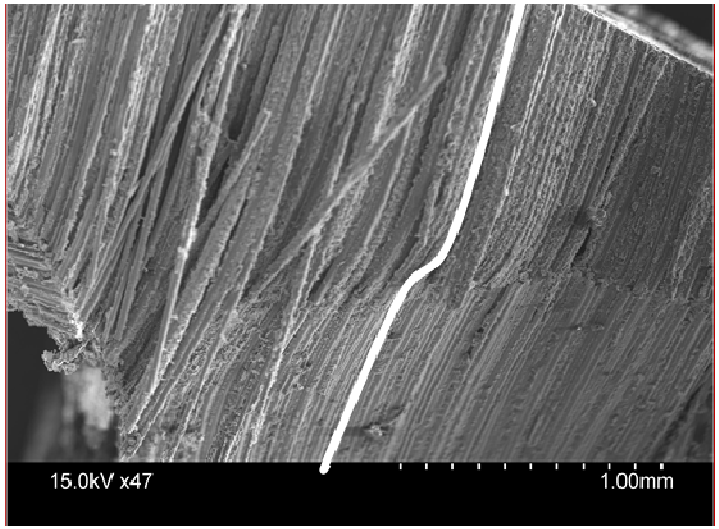
Effect of Compressive Loading on FRP

- **Post-compression images of the surface of FRP**
- **Visible Splitting**
  - Splitting may lead to other failure modes such as micro-buckling and kinking
  - Intrusion of moisture, stiffness degradation



Stages of Failure under compressive loading (1)

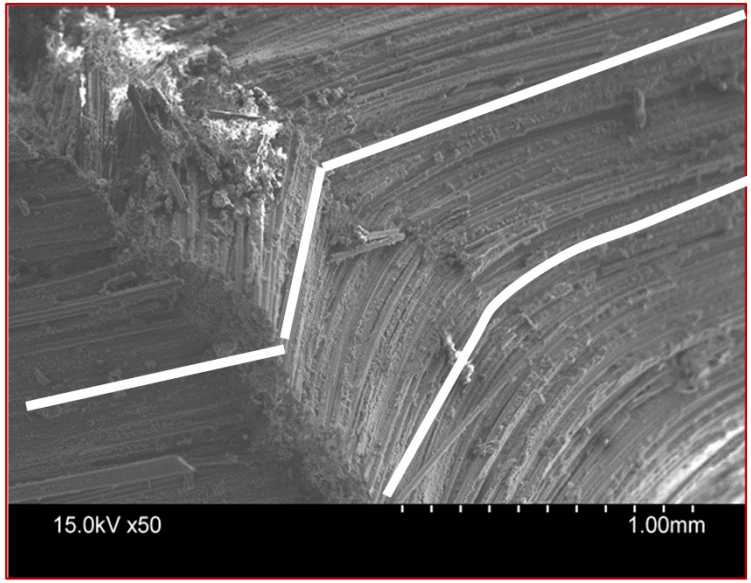


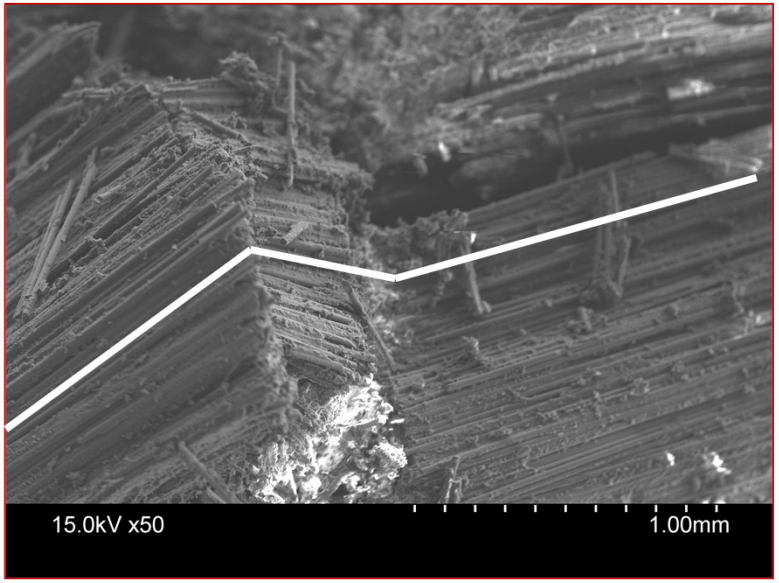


Dominant failure mode of long fiber is micro-buckling that leads to compressive failure of composite structures

- **Locally misaligned fibers**
- **Presence of voids**
- **Splitting due to matrix fracture**

Stages of Failure under compressive loading (2)



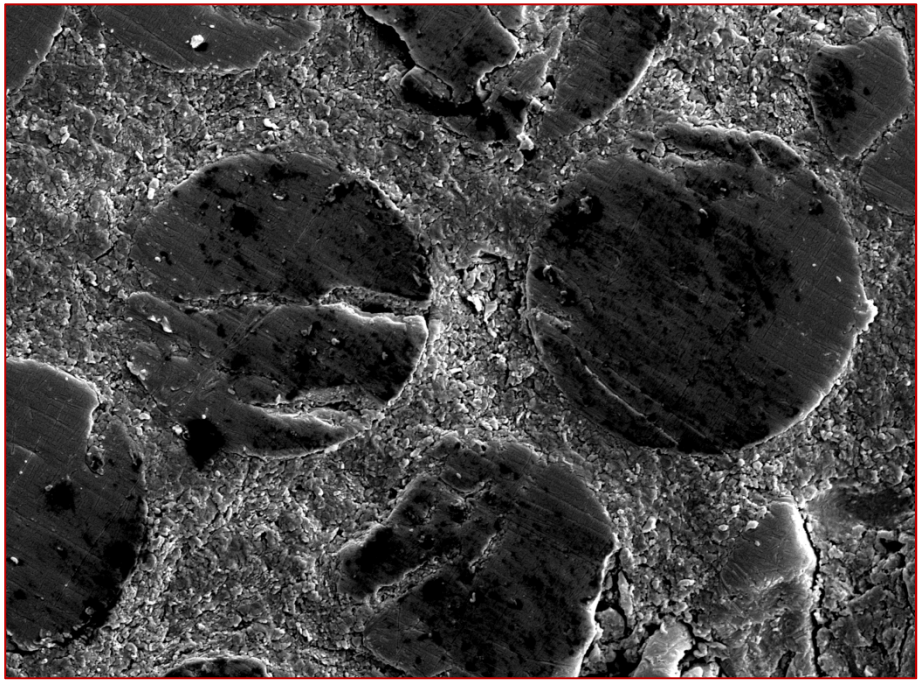


After inflection point forms (Previous slide), Kink forms, followed by a kink band.

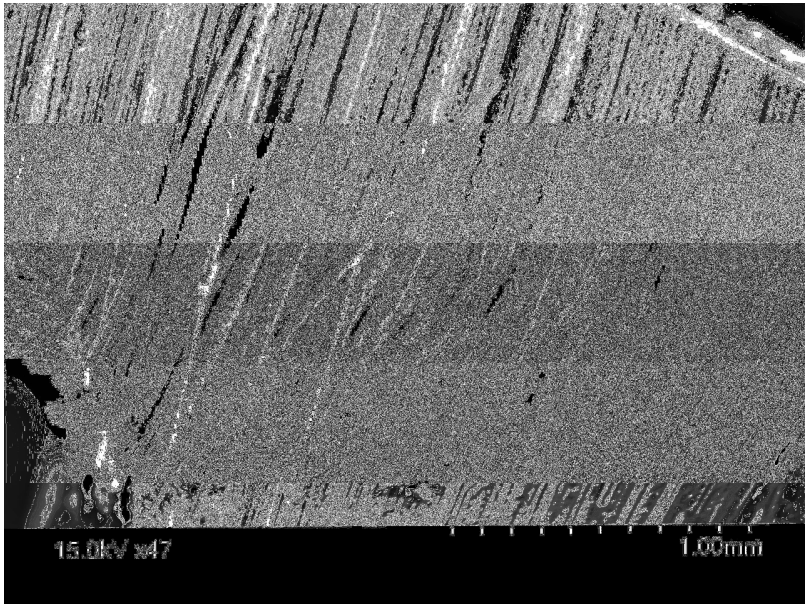
Effect of Moisture on FRP Matrix

Moisture exposed at 100° C for 220 days.

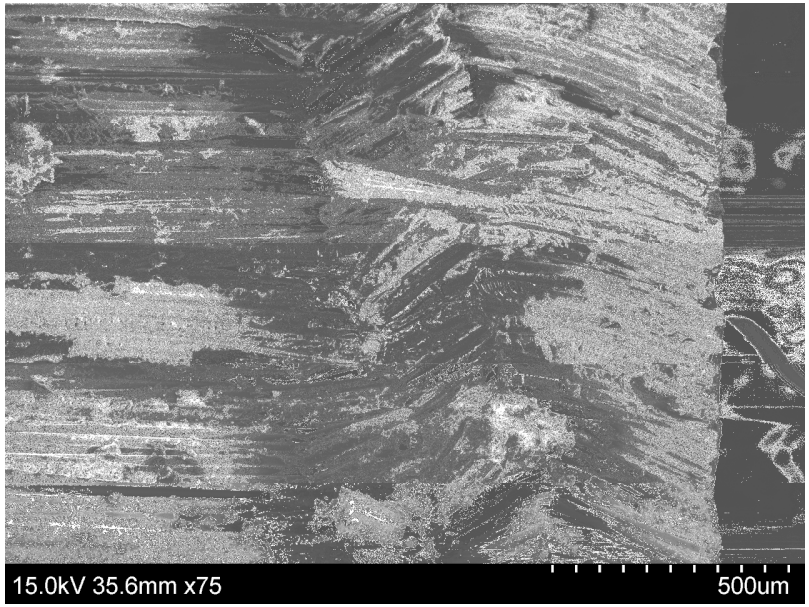
- Trace of water protrusion on the matrix and around the fiber.
- Signs of cracking and matrix degradation after aging compared to as received (previous slide)



Effect of Moisture on FRP Matrix



As Received
Loaded in
Compression



Exposed at 100° C for 220 days.
Loaded in Compression
Moisture exposure compromised matrix
and resulted in severe kinking

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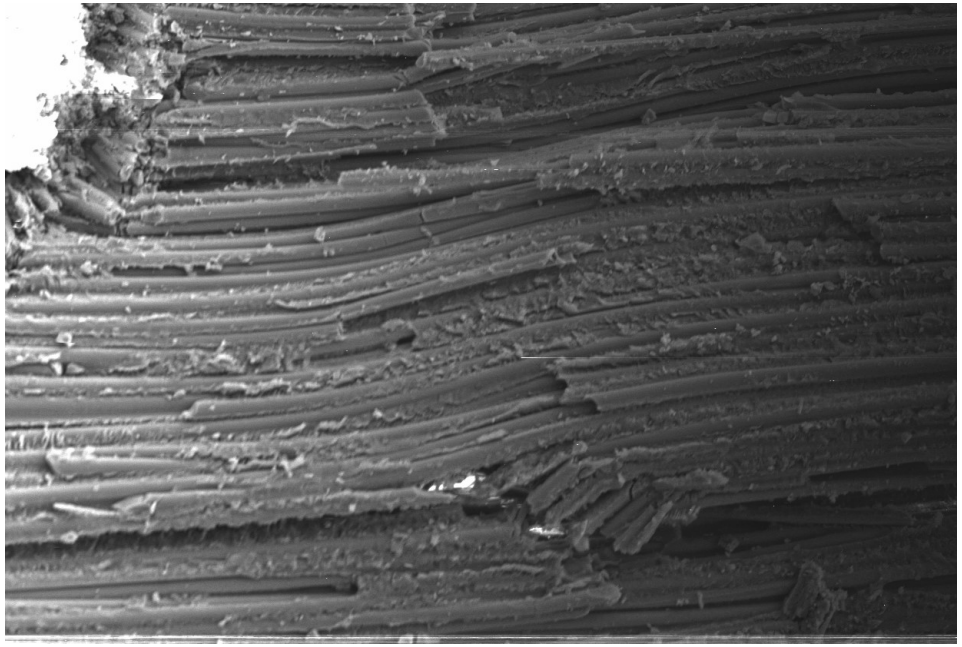
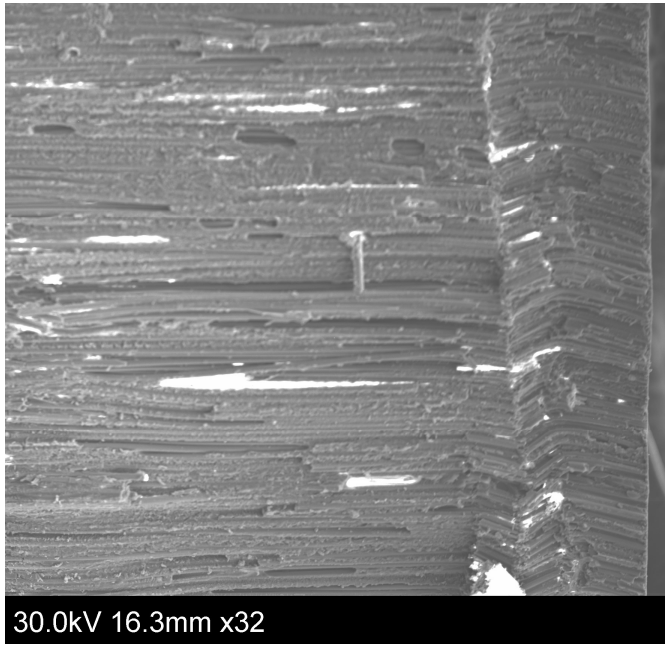
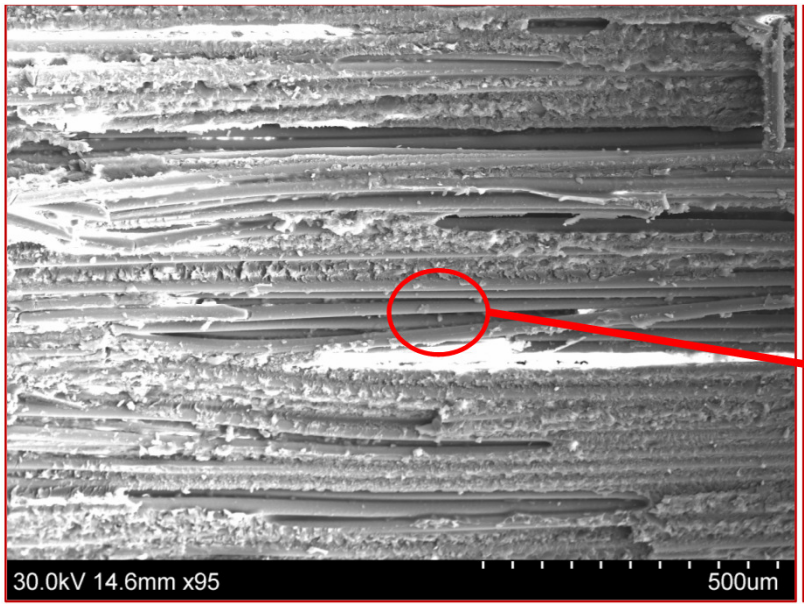
Effect of Moisture on FRP Matrix

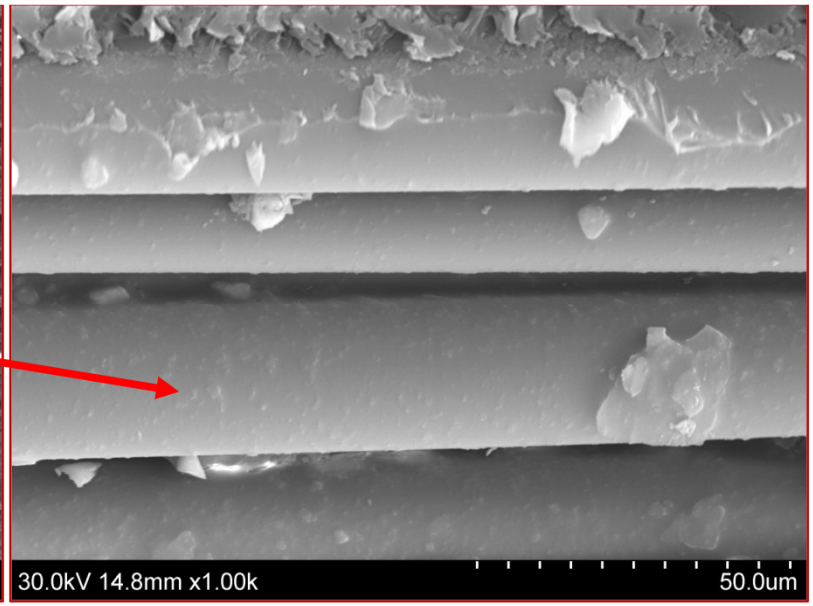




Effect of Environmental Exposure & Compressive Loading on Matrix



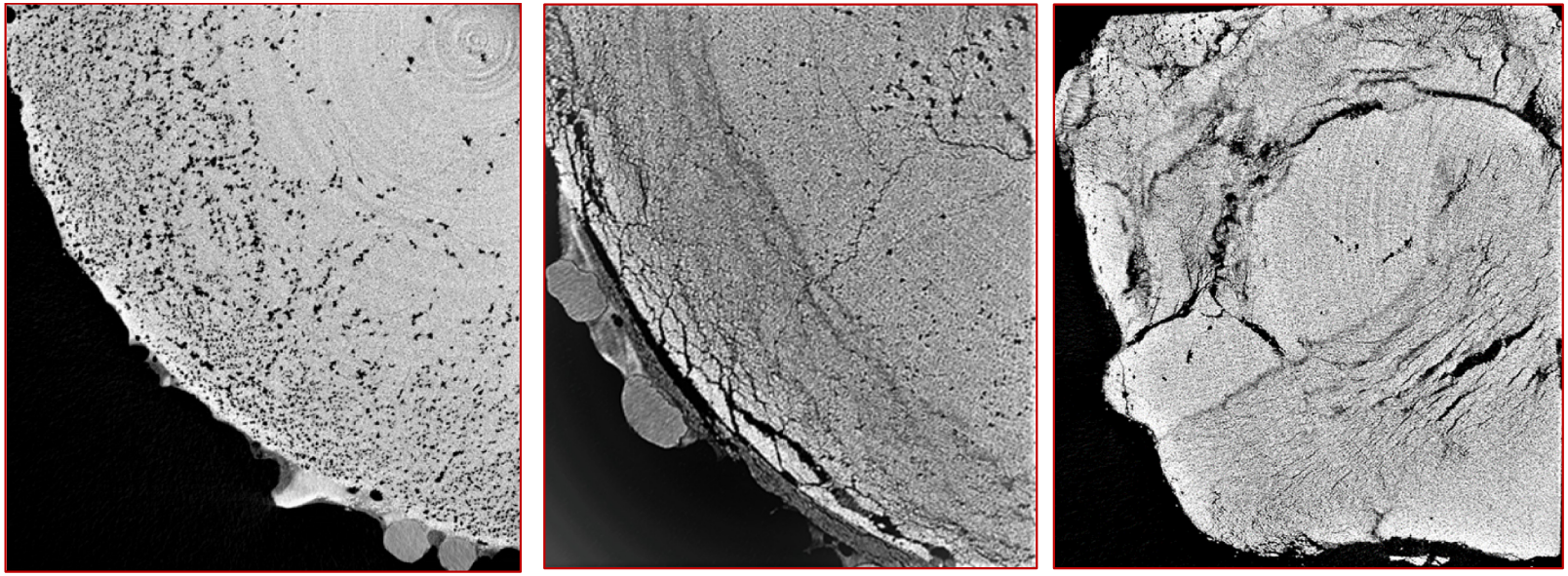
Quasi-static compression splitting failure mode of #5 Moisture exposed at 100° C for 220 days



Close up on splitting failure mode showing de-bonding of fibers after moisture exposure

Exposure caused early failure of matrix!

Effect of Moisture & Compression



X-ray Images of FRP. Left as received #5 . Middle as received tested in compression. Right moisture exposed tested in compression.

Surprisingly failure load reduced by only 15% for RHS, but modulus decreased substantially. Preliminary results suggest that effect is size dependent, with smaller bars exhibiting lesser degradation due to exposure!

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. Drivability

Concerns

- Less Efficient Driving
  - High damping
  - Low stiffness
- Integrity
  - Localized low strength

WEAP

Demonstration

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)

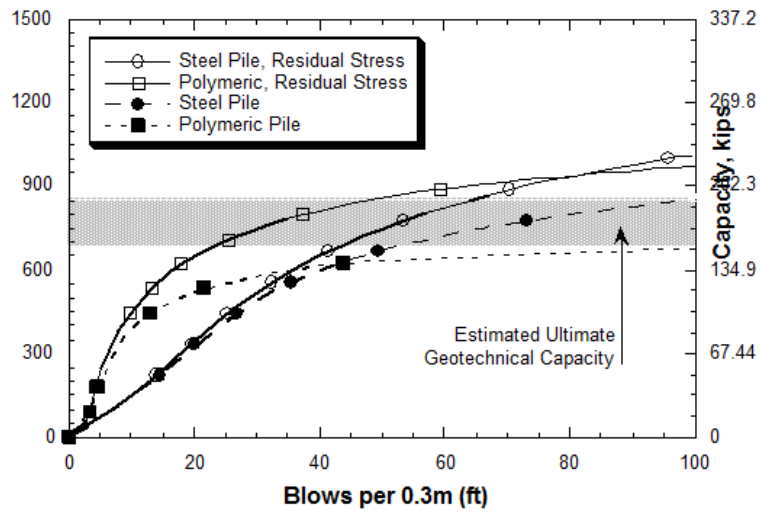
Effect of Residual Stress Analysis

Steel

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

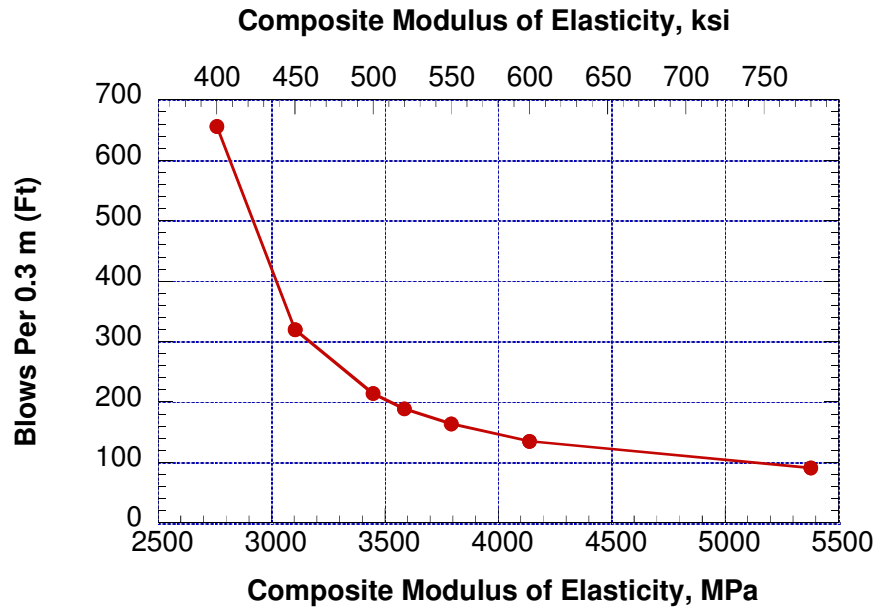
HDPE

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



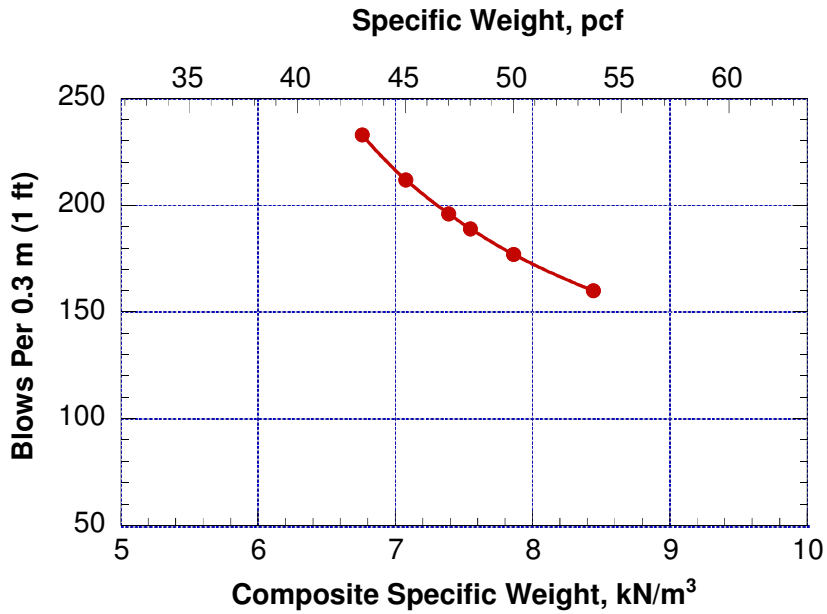
Effect of Modulus of Elasticity on Drieability

- 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 Unit Weight on Driveability

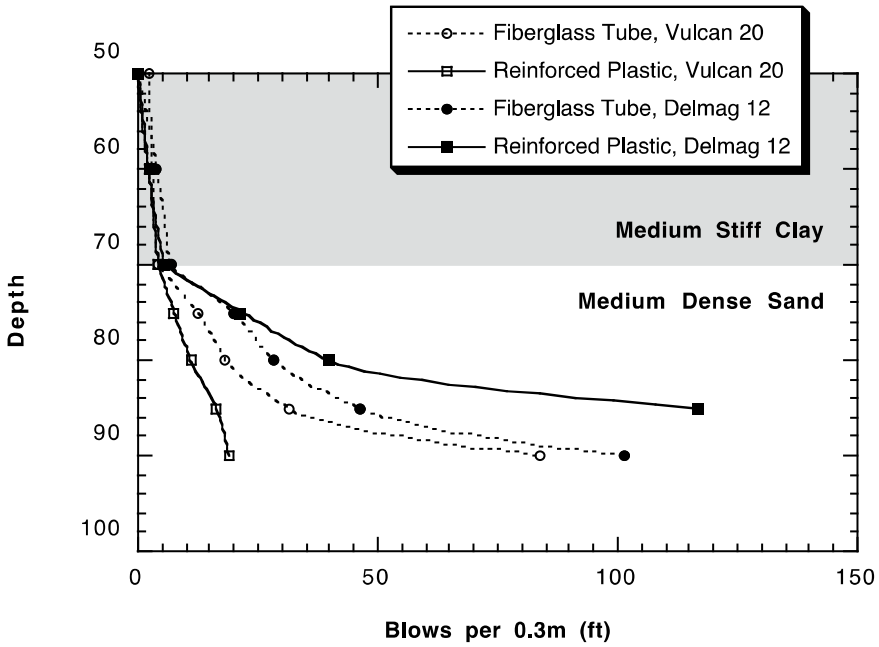
- Blows corresponding to a fixed capacity are plotted
- Damping ratios and Modulus kept constant
- **Because of foaming, the unit weight varies within the cross section and from one pile size to another.**



Effect of Hammer Type

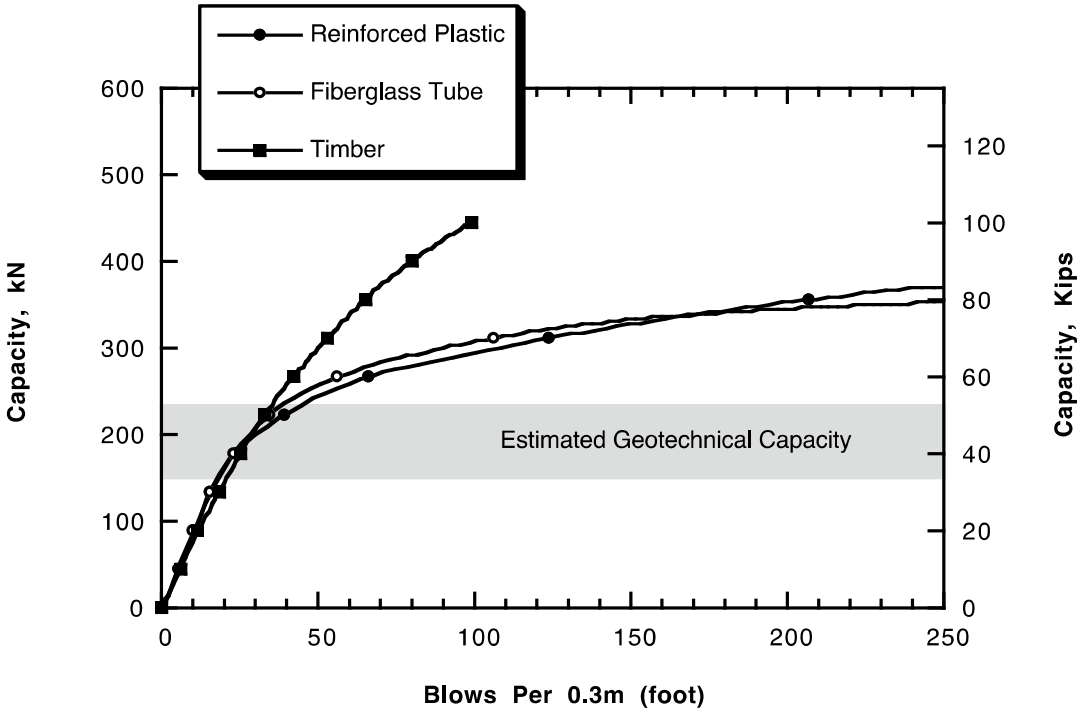
Single Acting Hammer

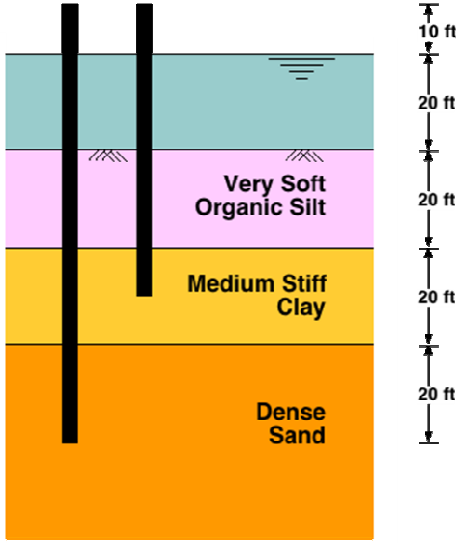
- The dynamic force exerted is shorter in duration than a diesel hammer
- heavier rams and shorter strokes
- stroke and efficiency are not dependent on the soil/pile stiffness



Vulcan 20, enthru = 42.5 kJ (31.5 kip-ft)
Delmag 12 diesel, enthru 40.5 kJ (30 kip-ft)

Parametric Studies Using WEAP

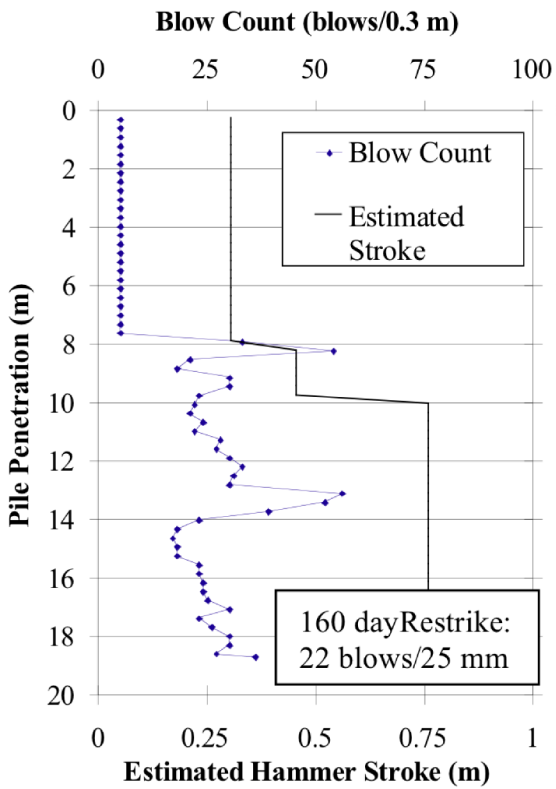




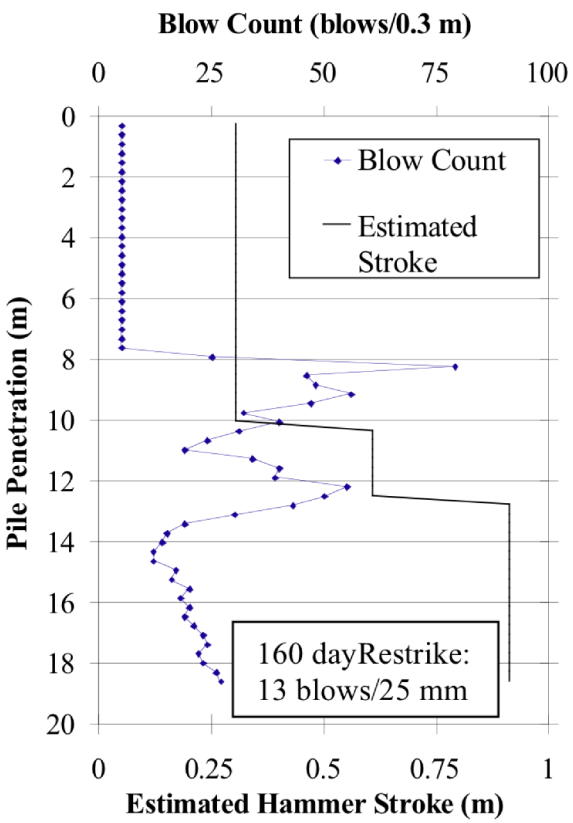
Field Demonstration

- Installed 14 piles in Port Newark
  - L = 60 ft
  - D = 16 in
- 5 manufacturers
- Dynamic Monitoring
- Load tests on instrumented piles

Drivability (FRP Reinforced)

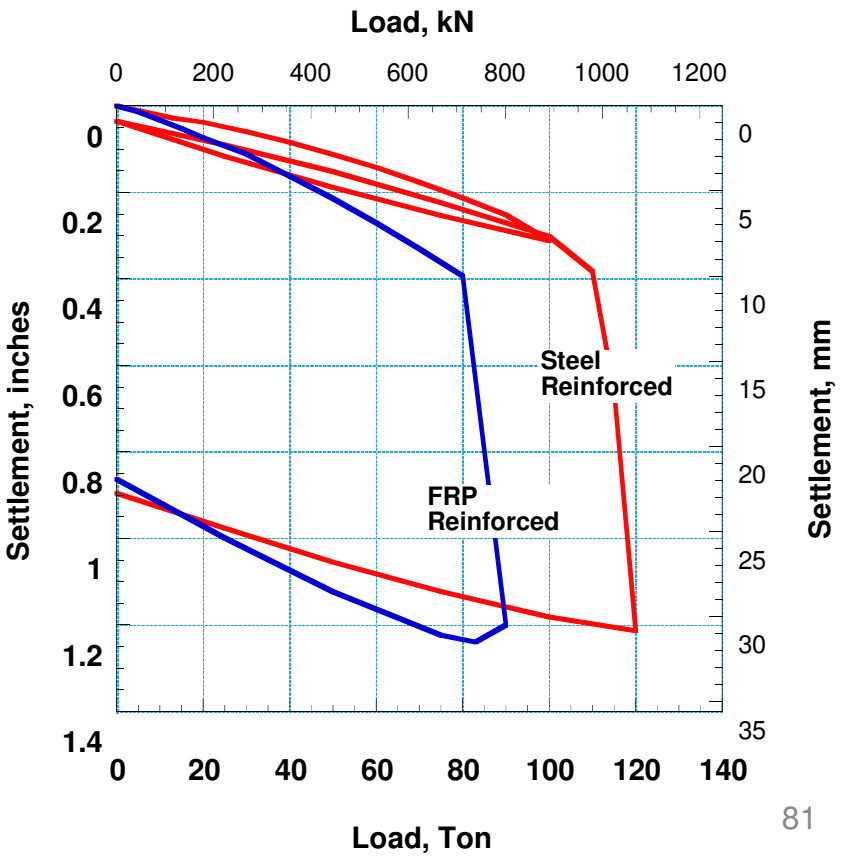


Drivability (Steel Reinforced)



6. Load Tests

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 Hurricanes

- 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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