

Natural Fiber Reinforced Concrete

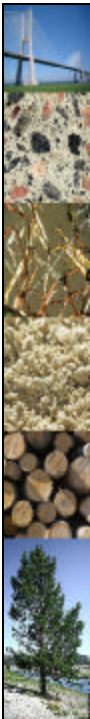
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4/2/2007

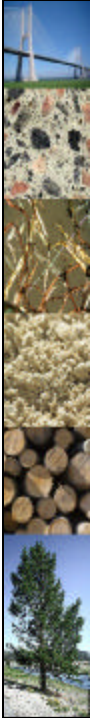
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Overview

- Fiber reinforced concrete
- Types of natural fibers
- History of natural FRC
- Wood pulp fiber composition and processing
- Wood pulp FRC
 - Fresh properties
 - Mechanical properties
 - Durability
- Future research and conclusions

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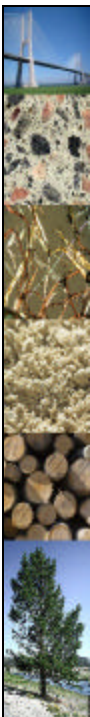
Fiber Reinforced Concrete

- Factors controlling performance of composites
 - Physical properties of reinforcement and matrix
 - Strength of bond between reinforcement and matrix
- Characteristics of fiber reinforced systems
 - Fibers distributed through given cross section, reinforcement bars only placed where required
 - Fibers are short and closely spaced, reinforcing bars are continuous
 - Small reinforcement ratio when compared to reinforcement bars

$$\text{Reinforcement Ratio} = \frac{\text{Area of Reinforcement}}{\text{Area of Concrete}}$$

(PCA, 2006)

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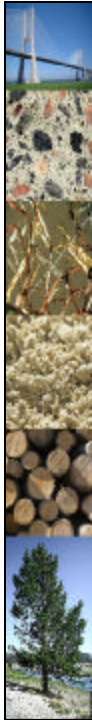


Fiber Reinforced Concrete

- Advantages
 - Easily placed
 - Cast
 - Sprayed
 - Less labor intensive than placing rebar
 - Can be made into thin sheets or irregular shapes
 - Used when placing rebar is difficult
- Disadvantages
 - Efficiency factors as low as .4 2-D (spray placement method), or .25 3-D placement (casting method)
 - Not highly effective in improving compressive strength

(PCA, 1991)

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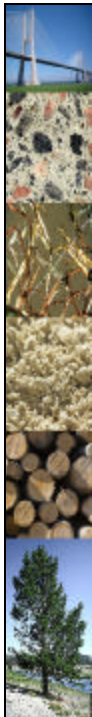


Comparison of Fiber Types and Properties

Fiber Type	Diameter, .001 in.	Specific Gravity	E, ksi x1000	Tensile Strength, ksi	Strain at Failure, %
Steel					
High Tensile	4-40	7.8	29	50-250	3.5
Stainless	.4-13	7.8	23.2	300	3
Glass	.4-.5	2.5-2.7	10.44-11.6	360-500	3.6-4.8
Polymeric					
Polypropylene	20-160	0.9	0.5	80-110	8
Polyethylene	1-40	0.96	.725-25	29-435	3-80
Polyester	.4-3	1.38	1.45-2.5	80-170	10-50
Amarid	.4-.47	1.44	9-17	525	2.5-3.6
Asbestos	.0008-1.2	2.6-3.4	23.8-28.4	29-500	2-3
Carbon	.3-.35	1.9	33.4-55.1	260-380	.5-1.5
Natural					
Wood cellulose	.8-4.7	1.5	1.45-5.8	44-131	-
Sisal	<8	-	1.89-3.77	41-82	3-5
Coir (Coconut)	4-16	1.12-1.15	2.76-3.77	17-29	10-25
Bamboo	2-16	1.5	4.79-5.8	51-73	-
Jute	4-8	1.02-1.04	3.7-4.64	36-51	1.5-1.9
Akwata	40-160	0.96	.076-.464	-	-
Elephant Grass	17	-	.716	26	3.6

(PCA, 1991)

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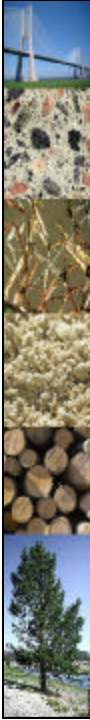
Types of Natural Fibers

- **Sisal (Castro, 1981)**
 - From AgaveSisalana in Mexico
 - Durability problems caused by chemical decomposition in alkaline environment
- **Coir (Balaguru, 1985)**
 - Coconut husks
 - Very durable to natural weathering
 - Increases modulus of rupture of concrete (MOR)
- **Bamboo (Ghavami 2005; Rodrigues, 2006)**
 - E is very similar to that of concrete
 - Susceptible to volume changes in water
 - Increases ultimate tensile strength and MOR
- **Jute (Balaguru, 1985)**
 - Grow in India, Bangladesh, China, and Thailand
 - Increases tensile, flexural and compressive strengths, as well as flexural toughness
- **Akwara (Balaguru, 1985)**
 - Abundant in Nigeria
 - No dimensional changes due to variations in water
 - Alkali resistant
 - No changes in flexural or compressive strengths
 - Impact strength 5 to 16 times greater than unreinforced cement matrix
- **Elephant Grass (Balaguru, 1985)**
 - Very durable – good rot and alkali resistance as well as small dimensional changes
 - Increases flexural and impact strength



(Longwood Gardens)

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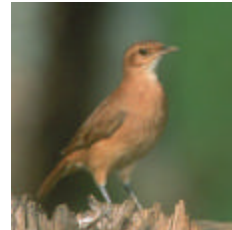


History of Natural Fiber Reinforcement

- Egyptians used straw in making mud bricks 1200-1400BC (Exodus 5:6)
- 2500 BC asbestos fibers used in Finland to make clay pots (Active Asbestos)
- Hornero bird native to South America builds nests out of straw and clay (Mehta, 2006)
- Replacement for asbestos

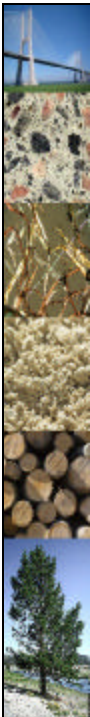


http://www.sci.tamucc.edu/~sterba/brazil04/2/109_0975.htm



<http://www.mangoverde.com/birdsound/pages/pic107-40-2.html>

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Current Uses

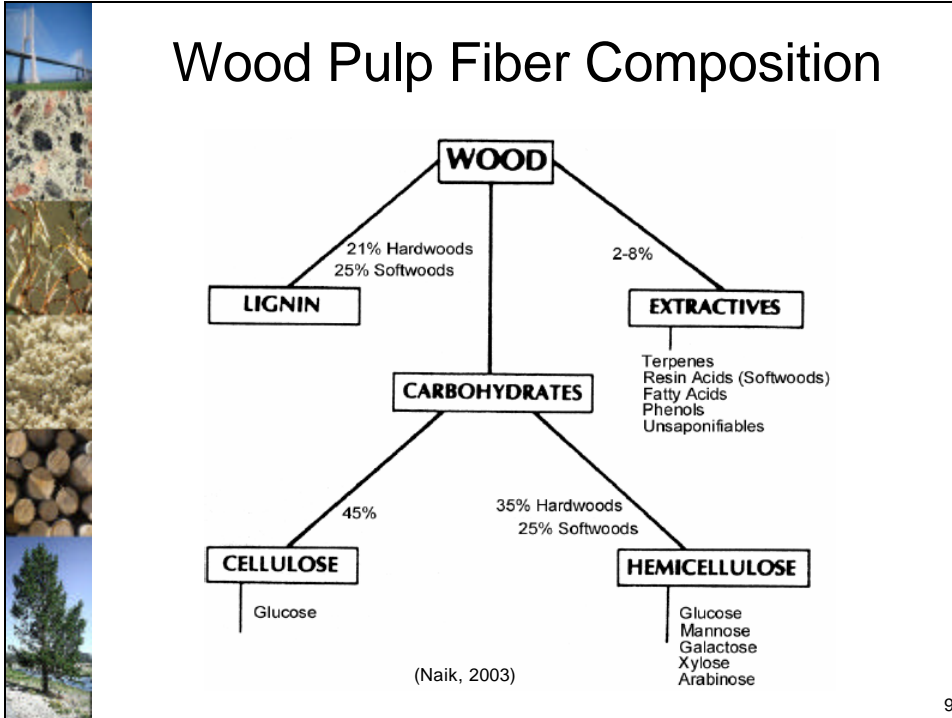
- Fiber Cement Board – James Hardie
 - Siding
 - Backer board
 - Roofing materials
 - Non pressure pipe
- Buckeye Technologies
 - UltraFiber 500
 - Slab on grade concrete
 - Precast concrete
 - Decorative concrete
 - 85% crack reduction
 - Improved hydration
 - Improved freeze/thaw resistance



(Coutts, 2005; James Hardie; Buckeye Technologies)

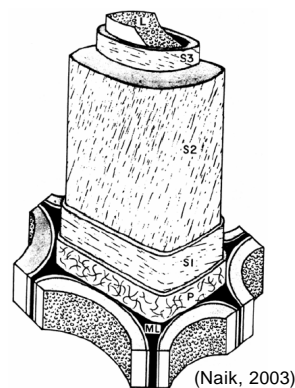
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Wood Pulp Fiber Composition



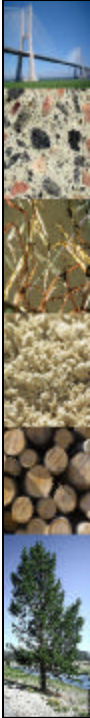
Wood Pulp Fiber Composition

- Cellulose – $(C_6H_{12}O_5)_n$
 - n degree of polymerization
 - 600-1500 for commercial wood pulps
 - Determines the character of the fiber
 - As cellulose increases fiber tensile strength and E increase linearly
- Hemicelluloses – polysaccharides of five different sugars
 - Easier to degrade than cellulose
 - Highly variable with fiber type
- Lignin – complex polymer composition
 - Binds wood together
 - Found in the middle lamella
 - Used in concrete as a set retarder
- Extractives
 - No physical structure
 - Give properties such as color, odor, taste
 - Some can be incompatible with concrete



ML – middle lamella
 P – primary wall
 S – secondary wall
 L - lumen

(TAPPI; Young)



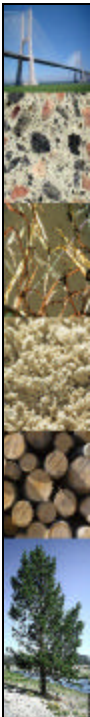
Wood Pulping Process

Mechanical Pulping	Chemical Pulping
By mechanical energy (small amount of chemicals and heat)	By chemicals and heat (little or no mechanical energy)
Yield*: 85-95%	Yield*: 40-55%
Short, weak, unstable, impure fibers	Long, strong, stable fibers
Good print quality	Poor print quality
<ul style="list-style-type: none"> • stone groundwork • refiner mechanical pulp • thermomechanical pulp 	<ul style="list-style-type: none"> • kraft (alkaline) • sulfite (acidic) • soda
25-31% lignin by mass	3-8% lignin by mass or 0-1% if bleached
SG=.5 due to open lumen	SG=1.5 due to collapsed lumen

(Naik, 2003; Mohr, 2005)

*Yield: weight of pulp/weight of wood (oven dry)

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Fresh Properties

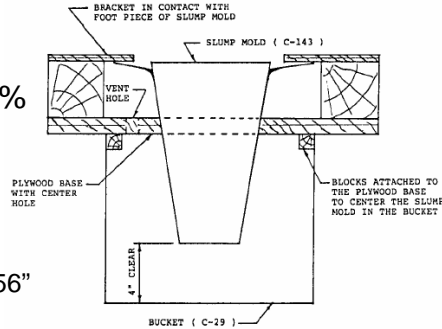
- Workability
- Setting time
- Cement hydration
- Fiber clumping/consolidation
- Shrinkage
 - Plastic
 - Free
 - Drying
- Internal curing and autogenous shrinkage

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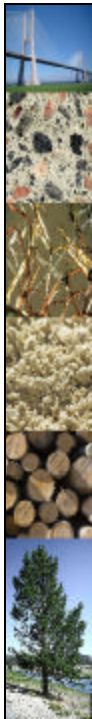


Workability

- Addition of fibers decreases workability due to an increase in surface area
- Low fiber fractions (<1% by mass) can significantly reduce slump
 - Control 9.25" w/c=.47
 - .8% (by mass) fibers 2.56" w/c=.47
- ASTM C995 – better indicator for workability than slump for FRC placed by vibration
 - Time of flow = 8-15 sec recommended for FRC (Naik 2004)

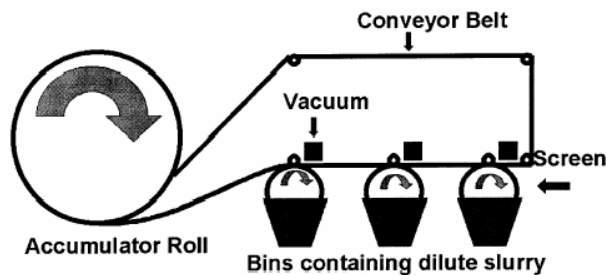


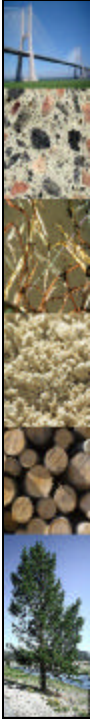
(ASTM C995)



Slurry Dewatering Process

- Used in high fiber fractions, normally fiber cement board (9% by mass)
- Initially high water content is produced to achieve high fiber content and uniform distribution
- Hatschek machine shown below (Kuder, 2003)

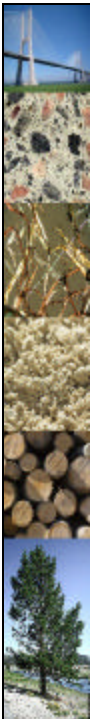
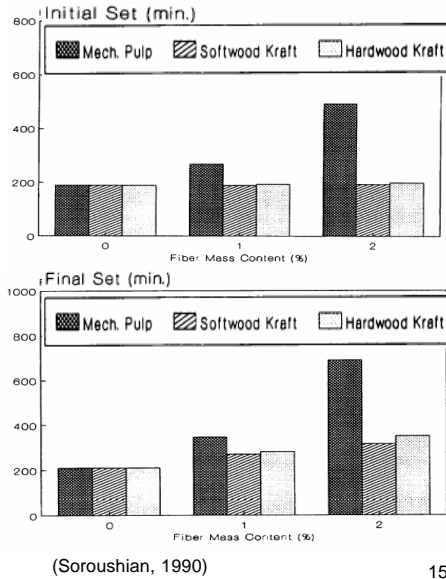




Setting Time

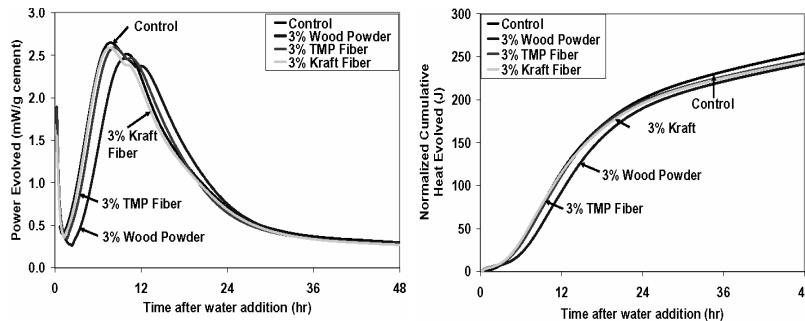
- Lignin can be used as a set retarder
- Fibers with lignin or other chemicals can have adverse effects on set time
- Fibers may absorb/desorb water from the cement matrix or atmosphere effecting set time
- Mechanical pulped fibers
 - 25-31% lignin
- Chemical pulped fibers
 - 0-8% lignin

(Naik, 2003; Soroushian, 1990)



Cement Hydration

- Addition of fibers has little to no effect on cement hydration



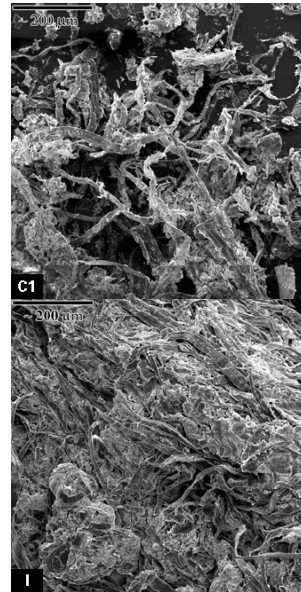
(Mohr, 2005)



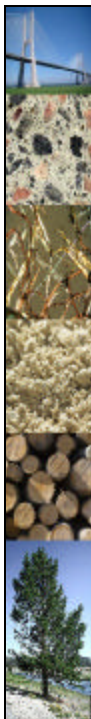
Fiber Clumping/Consolidation

- Pulp fibers have the tendency to clump together in water
- If fiber clumps are included in concrete they turn into weak spots in the concrete
- Research on mill residuals suggest that there is a direct relationship between ease of repulping and durability of the fibers
- Possible chemical coating of fibers to increase separation

(Chun, 2004)

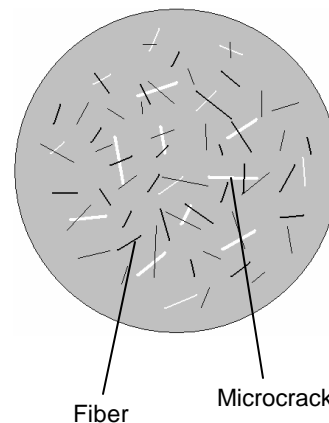


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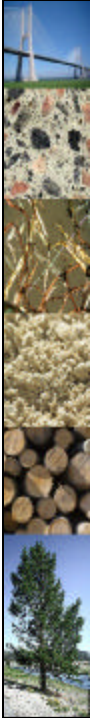


Plastic Shrinkage

- Occurs due to the loss of water at the surface faster than bleed water becomes available
- Concrete is too stiff to flow but not strong enough in tension to resist cracking (Kurtis, 2007)
- Addition of fibers can reduce plastic shrinkage cracking
 - Stops the spread of microcracks
 - Increases the tensile strength of concrete (Soroushian, 1991)

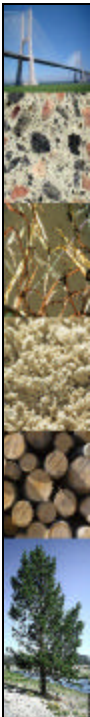
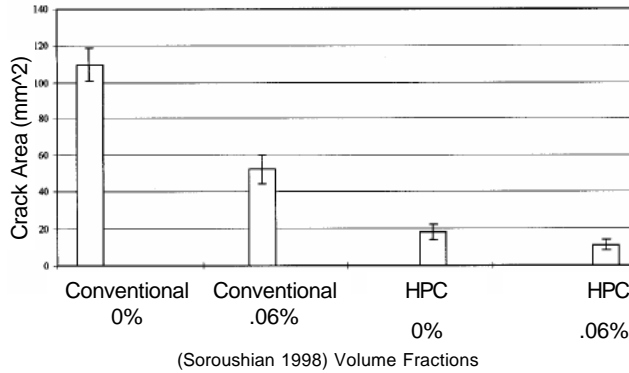


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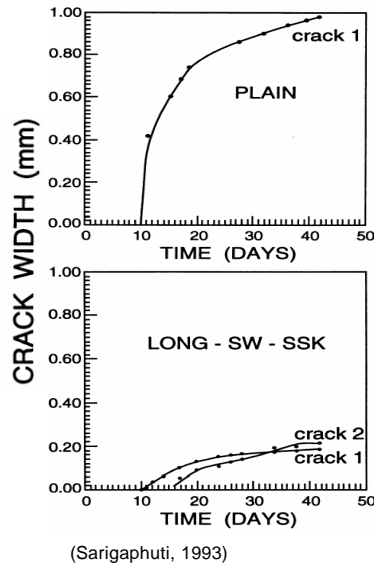
Plastic Shrinkage

- Cellulose fibers reduce plastic shrinkage in both normal and high performance concrete (Soroushian 1998)
- Polypropylene fibers normally used for crack resistance, pulp fibers could be more economical due to their low costs, even if higher fractions are required

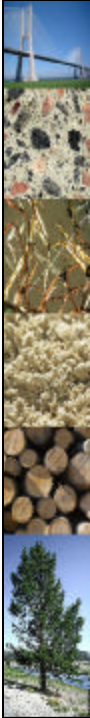


Other Types of Shrinkage

- Free shrinkage – pulp is hygroscopic and releases water upon drying, could account for dimensional change of the composite, Sarigaphuti's research suggest no effect
- Restrained drying shrinkage – due to restraining and minimization of evaporation, fibers can delay onset of cracking and reduce crack size (Rapoport, 2005)



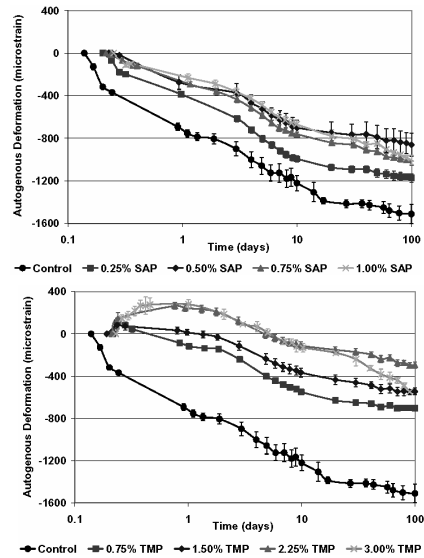
(Sarigaphuti, 1993)



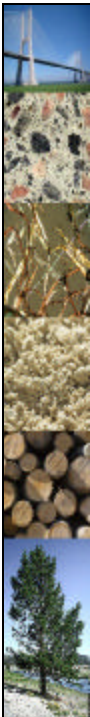
Internal Curing and Autogenous Shrinkage

- Mechanically pulped fibers minimize autogenous shrinkage even better than super absorbent polymers
- Chemically pulped Kraft fibers have minimal effects on autogenous shrinkage
- TMP fibers have detrimental consequences to compressive strength

(Mohr, 2005)



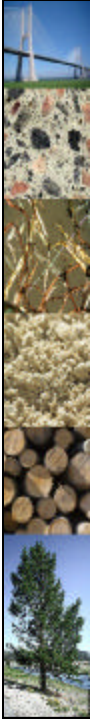
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Mechanical Properties

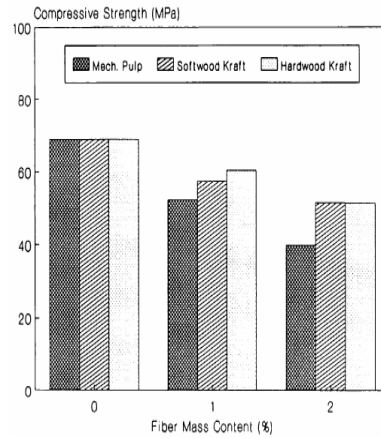
- Compressive strength
- Flexural strength
- Flexural toughness
- Impact strength

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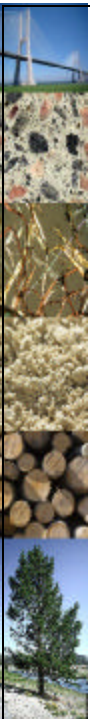


Compressive Strength

- High fiber content composites can have reduced compressive strengths
- Strength reduction most likely due to increased amount of entrapped air due to presence of fibers
- Most research agrees that volume fractions up to about 1% does not significantly effect compressive strength



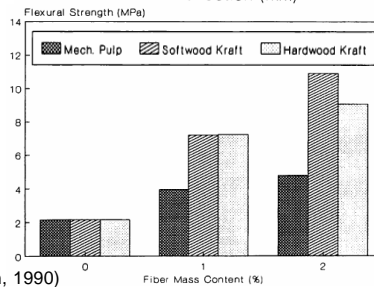
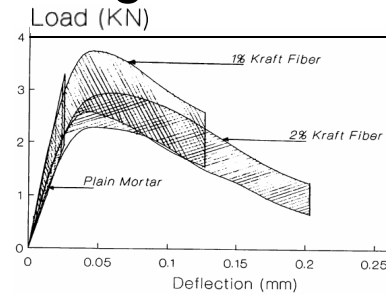
(Soroshian, 1990)



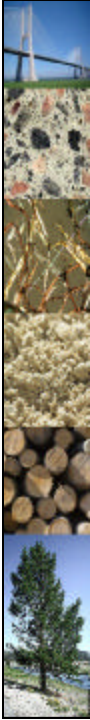
Flexural Strength

- In general, as fiber content increases so does flexural first crack and peak strength
- Influenced by moisture content of the composite
- Research disagrees on the optimum fiber content for peak strength
 - Varies between 6% to 20% by mass

(Mohr, 2005)

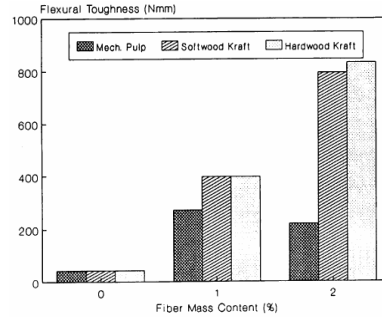


(Soroshian, 1990)



Flexural Toughness

- Toughness is defined as the amount of energy required to break a material (area under the load deformation curve) (Mehta, 2006)
- Addition of pulp fibers in concrete increases flexural toughness
- Normally toughness after first crack is compared
 - No clear method for measuring, can be very test specific
 - Japanese code JCI-SF
 - ASTM C1018
 - New method (El-Ashkar, 2006)
 - Identify first crack point
 - Unreinforced toughness subtracted
 - Use of indexes to describe the postcracking portion of the load-deflection curve



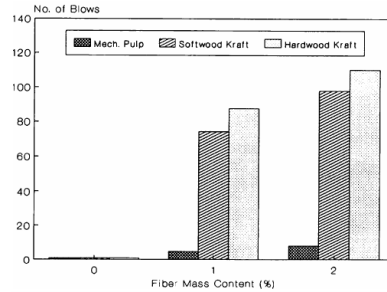
(Soroushian, 1990)

Impact Strength

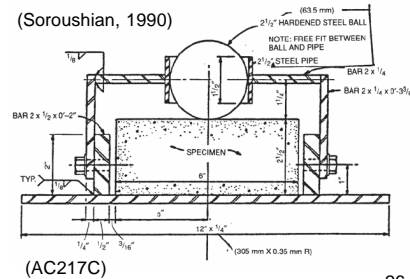
- Number of blows by a standard weight to crack or fail the composite
- Impact strength for fiber reinforced slabs is 3-18 times higher than plain mortar slabs
- Residual impact strength (I_{rs}) 1.37 for non reinforced cement and up to 3.91 for FRC

$$I_{rs} = \frac{\text{Energy absorbed at ultimate failure}}{\text{Energy absorbed at initiation of first crack}}$$

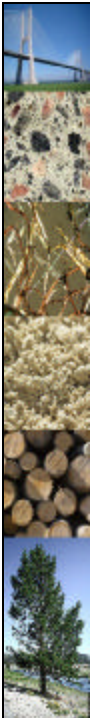
(Ramakrishna, 2005)

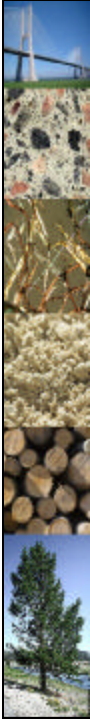


(Soroushian, 1990)



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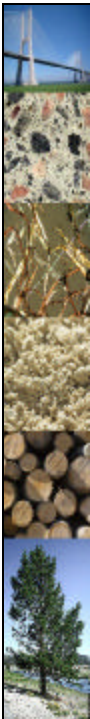




Durability

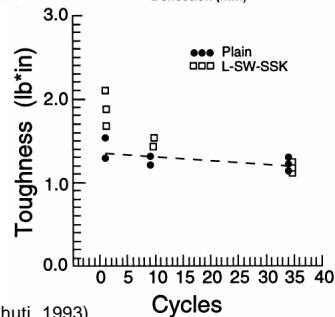
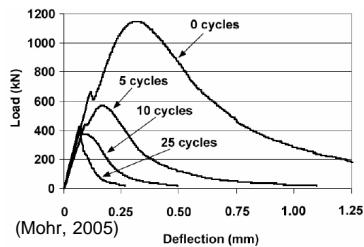
- Wet/dry exposure
- Fiber failure modes
- Freeze thaw resistance
- Permeability
- Durability improvements

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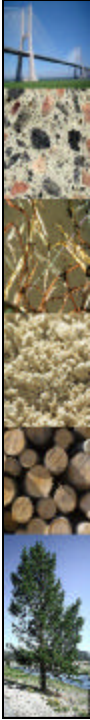


Wet/Dry Exposure

- After 25 wet/dry cycles on unmodified pulp fiber composites (Mohr, 2005)
 - 43-52% loss of first crack strength
 - 51-72% loss of peak strength
 - 97-99% loss of post cracking toughness
- Other research suggests only a 40% loss in flexural toughness and an increase in flexural strength (Sarigaphuti, 1993; Soroushian, 1994)



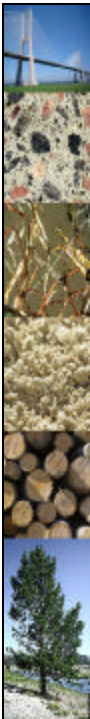
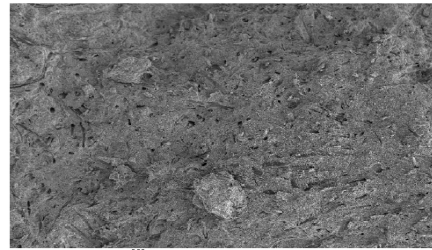
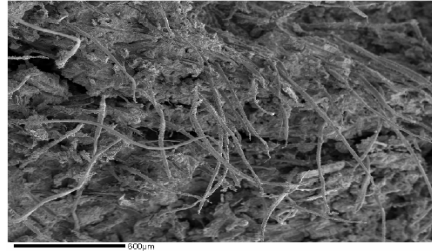
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Wet/Dry Failure Modes

- SEM micrograph of 0 cycles
 - fiber pullout method of failure
- SEM micrograph of 25 cycles
 - fiber fracture method of failure

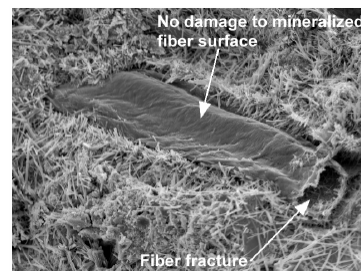
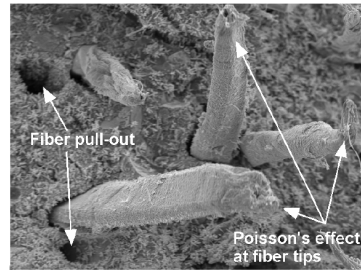
(Mohr, 2005)

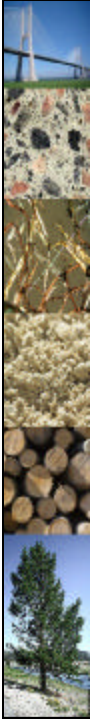


Fiber Failure

- Ductile failure at 0 cycles of wet/dry
 - Fiber pullout
 - Necking on fracture
- Brittle failure at 25 wet/dry cycles
 - Due to the mineralization of the fibers

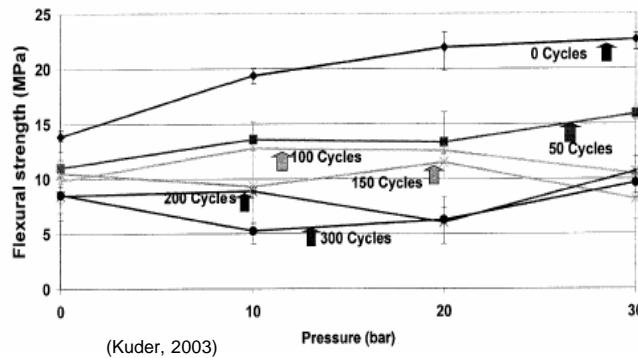
(Mohr, 2005)



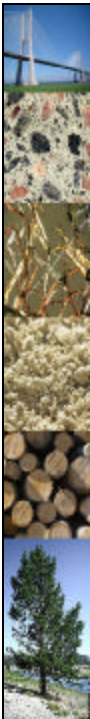


Freeze Thaw Resistance

- Fiber cement board and the effects of pressure treatment
- 9% cellulose fibers by mass
- Cellulose fibers increase freeze thaw durability 52% (icc Evaluation)

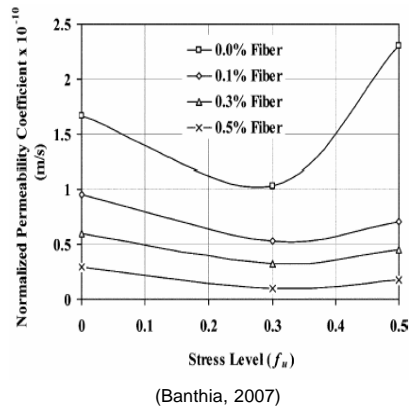


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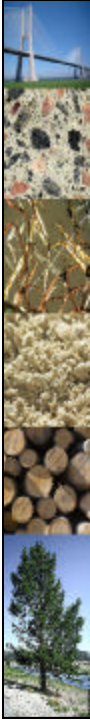


Permeability

- Fibers reduce permeability of unstressed concrete
 - Reduction is proportional to volume fraction
- Normal concrete permeability increases at .3 x f_c
- Increases in permeability are minimal until .5 x f_c for FRC
- Fibers are expected to increase overall durability due to decreased permeability (Banthia, 2007)



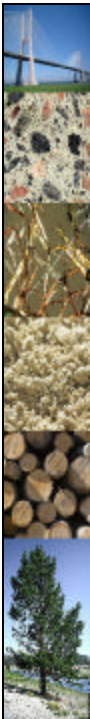
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Durability Improvement

- Pressure treatment on fiber cement board
- Reduction in w/c ratio to decrease porosity
- Addition of SCMs eliminated degradation due to wet/dry cycles (Mohr, 2005)
 - 30%, 50% Silica Fume
 - 90% Slag
 - 30% Metakaolin 235
 - 10% SF / 70% SL
 - 10% MK235 / 70% SL
 - 10% MK235 / 10% SF / 70% SL
- Chemically coated fibers

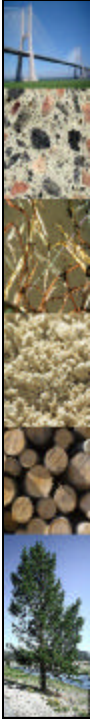
33



Conclusions

- Natural fibers offer many benefits for reinforcement
 - Low cost and abundant
 - Renewable
 - Non hazardous – replacement of asbestos
- Can improve characteristics of concrete
 - Increase flexural strength and toughness
 - Increase impact resistance
 - Reduce shrinkage and cracking
 - Improve durability by stabilization of microcracks and decrease in permeability

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Future Research

- Sources of pulp fibers
 - Thermomechanical fibers
 - Paper mill residual solids
- Optimal fiber ratios for specific uses
- Durability
 - Additional research on freeze thaw
 - Wet/dry cycle effects
- SCM addition

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