Optimization of Woven Carbon Fiber Reinforced Composites for Structural & Tribological Applications

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Map not to Scale
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RESIDENTIAL CAMPUS

ALL STUDENTS
ALLFACULTY
50% STAFF

Area 320 Acres (130 hectares)

Population ~ 13000

Academic Resources

Academic Departments:	**13**
Research Centers:	**9**
Interdisciplinary Programmes:	**10**
Service Centers:	**2**
Computer Services	
Educational Technology Services	
Other central facilities:	**12**

Academic Departments
(greater focus on teaching programmes)

Engineering

- Applied Mechanics
- Biochemical Engg. & Biotech.
- Chemical Engineering
- Civil Engineering
- Computer Sc. and Engg.
- Electrical Engineering
- Mechanical Engineering
- Textile Technology

Physical Sciences

- Chemistry
- Mathematics
- Physics

Humanities & Management

- Humanities and Social Sc.
- Management Studies

Research centres

(greater focus on sponsored research)

- Applied Research in Electronics
- Atmospheric Sciences
- Biomedical Engg.
- Energy Studies
- Instrument, Design & Development
- Industrial Tribology &Machine Dynamics
- Polymer Science and Engg.
- Rural Development & Technology
- Value Education in Engg.

My Major Research areas- Development of Polymer composites & nano-composites

- as antifriction materials-bearings, gears etc
- as friction materials-brake pads, shoes linings etc.

•Conventional Lubricants

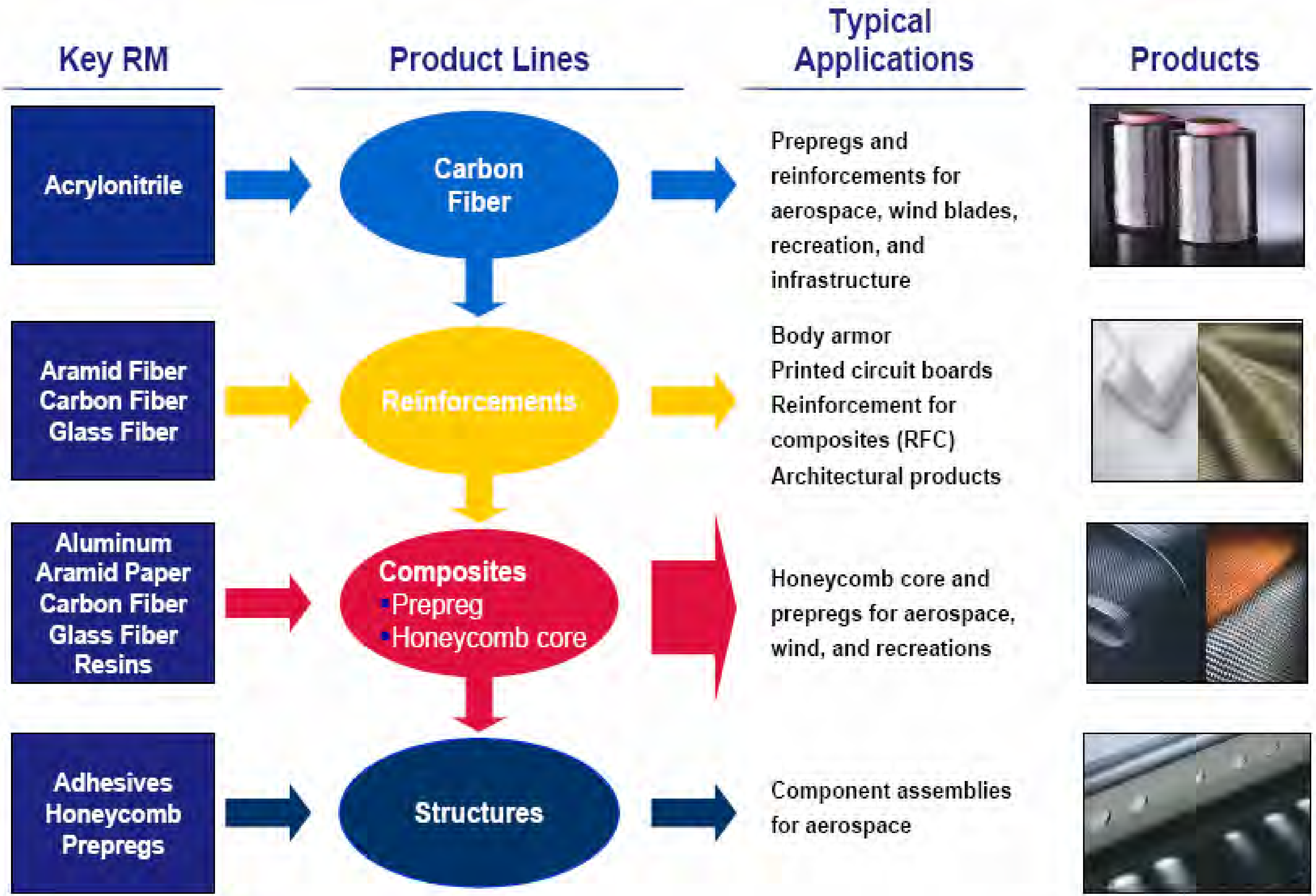
•Oil analysis as a condition monitoring tool

Optimization of Woven Carbon Fiber Reinforced Composites for Structural &Tribological Applications.

Presentation Outlay

- Polymer composites with Carbon fabric reinforcement- main applications
- Development of composites with variation in amount, weave & techniques
- Characterization of composites for physical & mech. properties
- Performance evaluation in adhesive wear mode
- Conclusions

High performance reinforcements in various applications

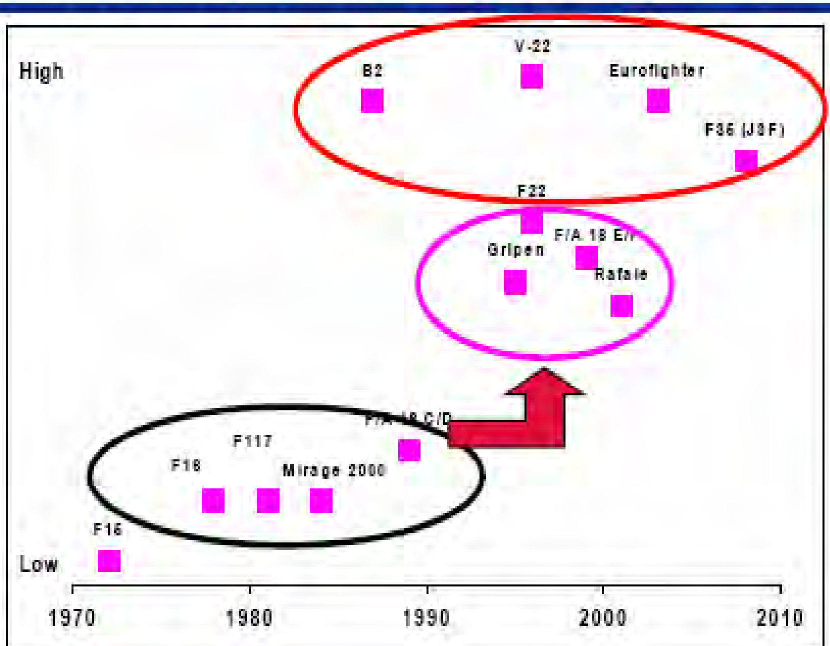


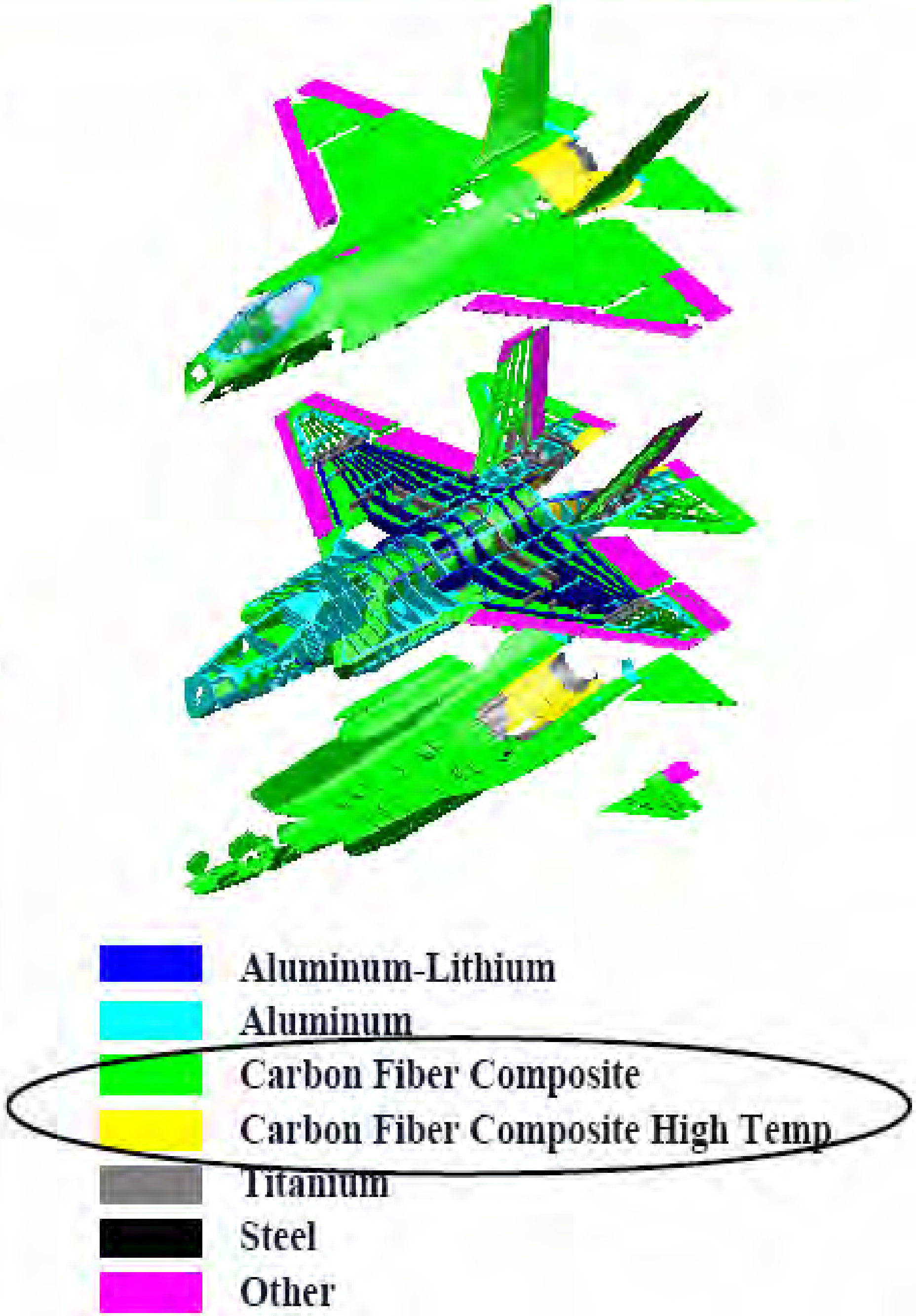
Composites in Aerospace

Trends/Position

- Growing penetration of composites
  - Lightweight, stiff and strong
  - Long life – no fatigue
  - No corrosion, low toxicity
  - Low coefficient of thermal expansion
  - Stealth

Composite Penetration – Step Function Gain






HS Carbon Fiber
IM Carbon Fiber
Secondary Structure Prepreg
BMI
Conductivity
Floor Panels
M21 prepreg
Septum Core
Thermoplastics
HexMC
Adhesives

Why Carbon fibers / fabric reinforcement in tribology ?

Amongst popular fibers such as CF, GF & AF etc, CF is the best because of :

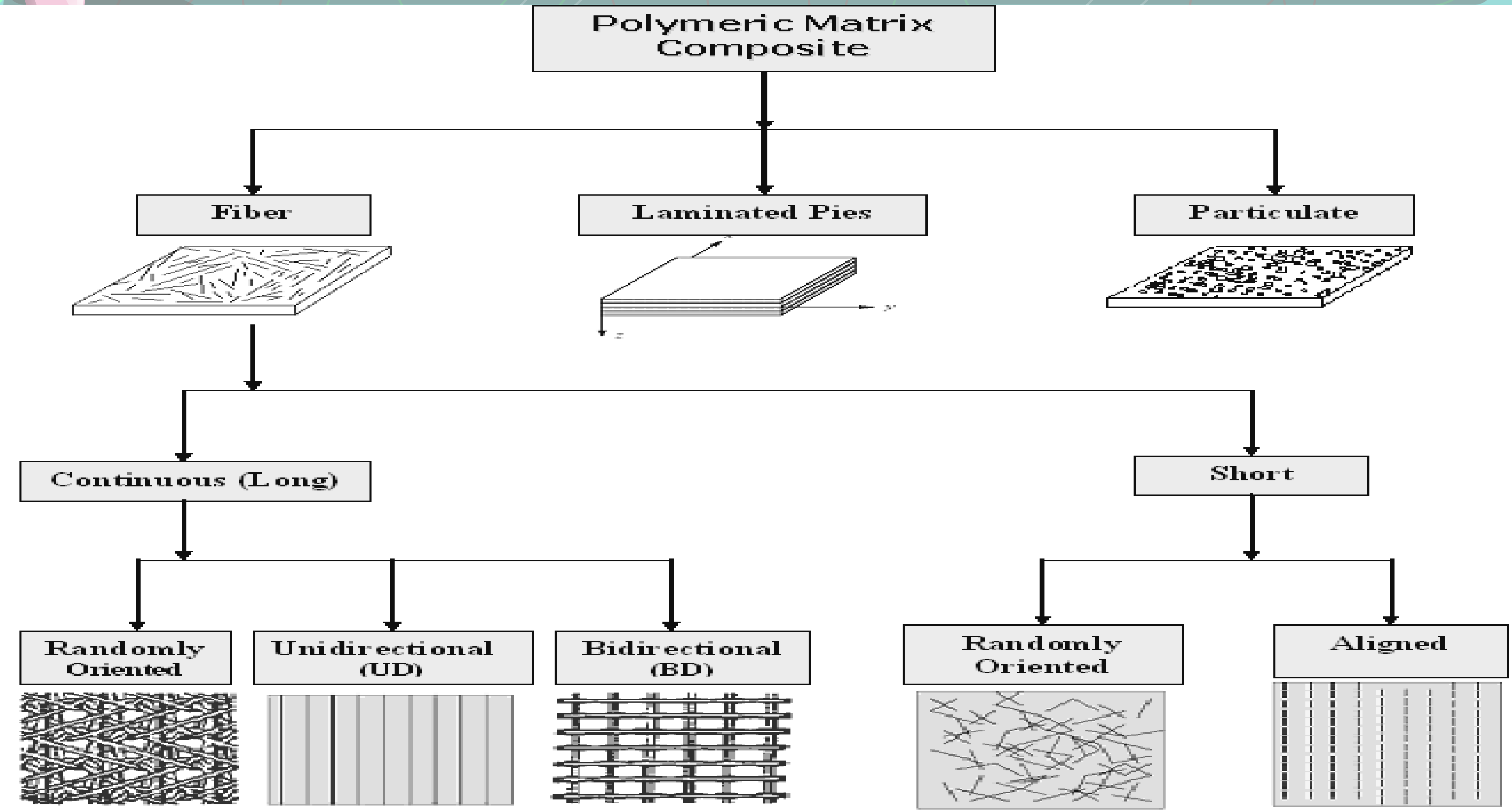
- Highest specific strength, modulus and stiffness
- Highest thermal stability.
- High resistance to oxidation
- High thermal conductivity hence least accumulation of heat at the sliding surface of a tribo-couple
- Self lubricating properties
- High fatigue resistance,
- Corrosion resistance etc

Introduction

Why Polymer composites in tribology ?

- Innovations in technology demand for better performance: conventional lubricants are ineffective.
- New class of solid lubricants/polymer composites show excellent performance where conventional lubricants cannot be considered.
- Extreme P,T, radiations, corrosive environment etc.
- Industries viz. paper, textile and food etc. where composites of high performance polymers (PEEK, PIs, PAI, PEI, PES, PPS etc) with reinforcements most favored.
- Most favored materials for tribo- components in space (vacuum, cryogenic, high temp conditions etc)

Types of Reinforcements



Reinforcement- v necessary for polymers & Fabric (BD) type-most favored (easy processing, & bi-directional strength). Drape property very imp for achieving complex shapes without wrinkles.

Challenges while designing BD composites for desired applications

Right selection of reinforcement & matrix

Right amount of fabric

Right weave of fabric

Right fiber orientation to the loading direction

Right processing technique

Present work –to achieve the best possible combination of

- Low friction
- High wear resistance
- High strength

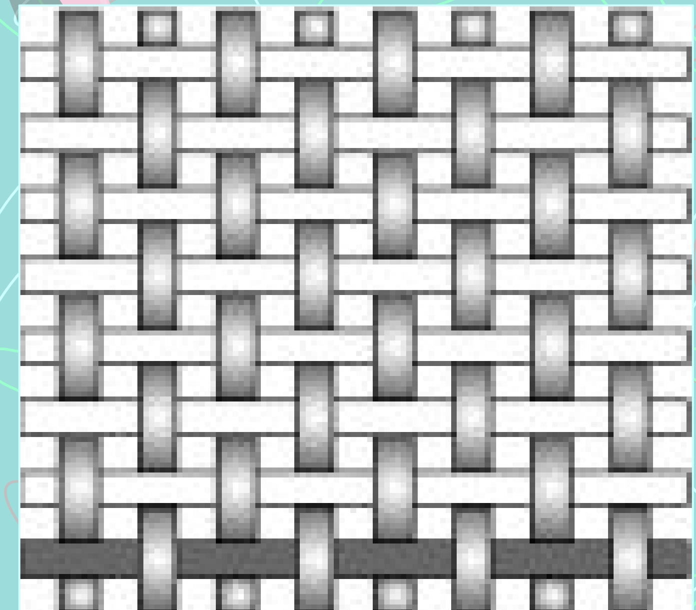
Objectives

Development of various series of composites using Polyetherimide (PEI) as a matrix and carbon fabric (CF) as a reinforcement with following variations in

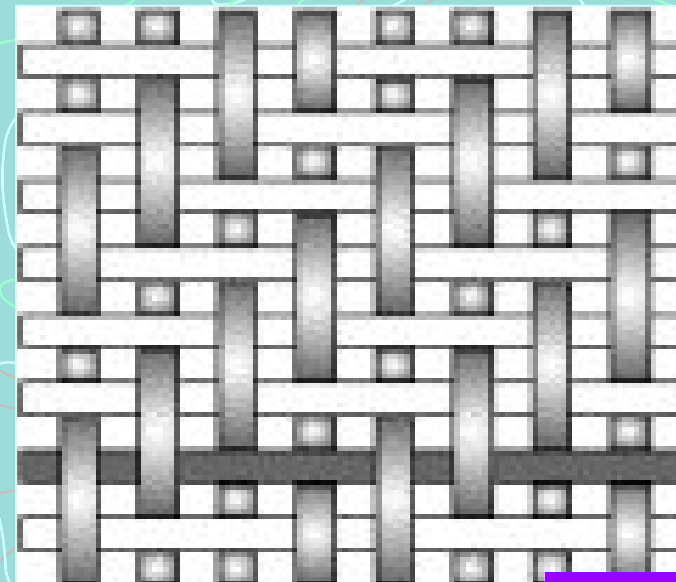
- Amount of fabric
- Weave of fabric
- Technique of processing of composites
- Orientation of fiber with respect to loading direction.

which would serve as guidelines to tailor composites with desired range of strength, modulus and tribo-properties.

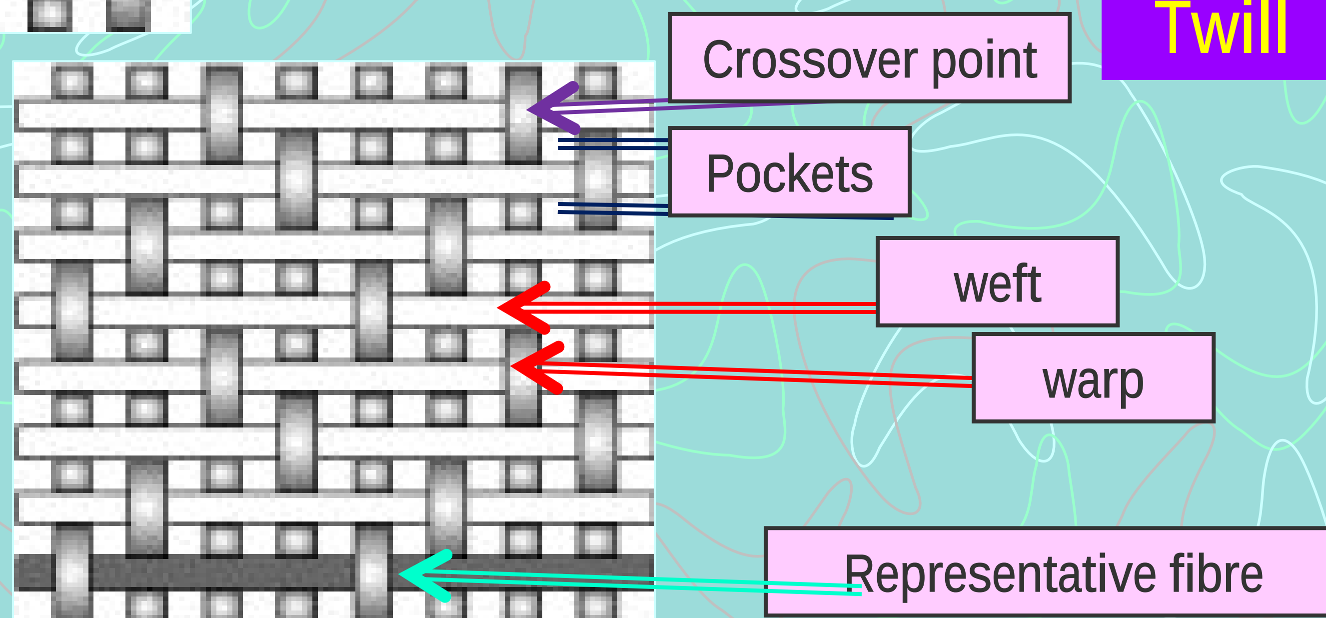
Types of Weaves Selected (Fibre Glast Ltd. USA.



Plain



Twill



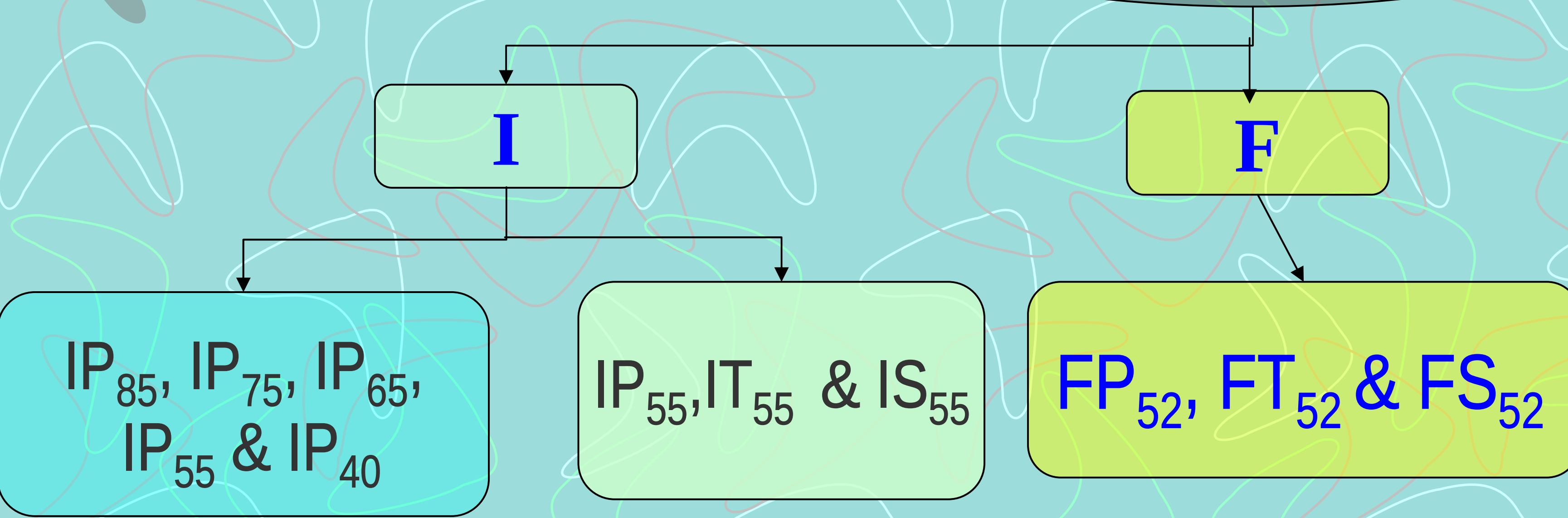
Satin (4 Harness)

Properties of fabrics measured in the laboratory

Carbon Fabric	Plain (P)	Twill (T)	Satin (4-H) (S)
Density (kg/m^3)	1850	1850	1850
Area (kg/m^2)	1960	1980	1930
*Tow**	*3K*	*3K*	*3K*
Tex	20	22	19
Denier	185	198	171
Crimp %	0.64	0.70	0.30
Count	28	26	31
Warp/inch & Weft/inch	12	16	14
Thickness (m)	0.0034	0.0034	0.0036
Bending Length (m)	0.072	0.059	0.05
Tensile strength (MPa)	0.3	0.147	0.12
Elongation %	1.25	1.85	1.52

* *Data by the supplier. Carbon fiber-PAN based high modulus type*

Scheme for Fabrication of Composites



- I and F – Impregnation and film technique
- IP, IT and IS- Impregnation technique with three different weaves of carbon fabric (P-for plain, T for Twill and S for Satin weave)
- FP, FT and FS- Film technique with different weaves of CF
- Subscripts 85, 75, 65, 55 and 40 for the amount of content of fabric (by vol. %) in the composites

Methodology for formulation of composites

Matrix selected-

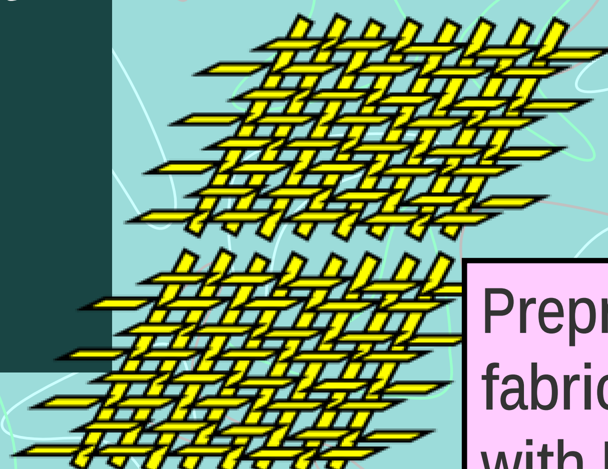
Polyetherimide (PEI) supplied by GE Plastics USA

High performance specialty polymer (amorphous yet ductile) with

- T_g- 217^{0}C
- T_m (380-400°c)

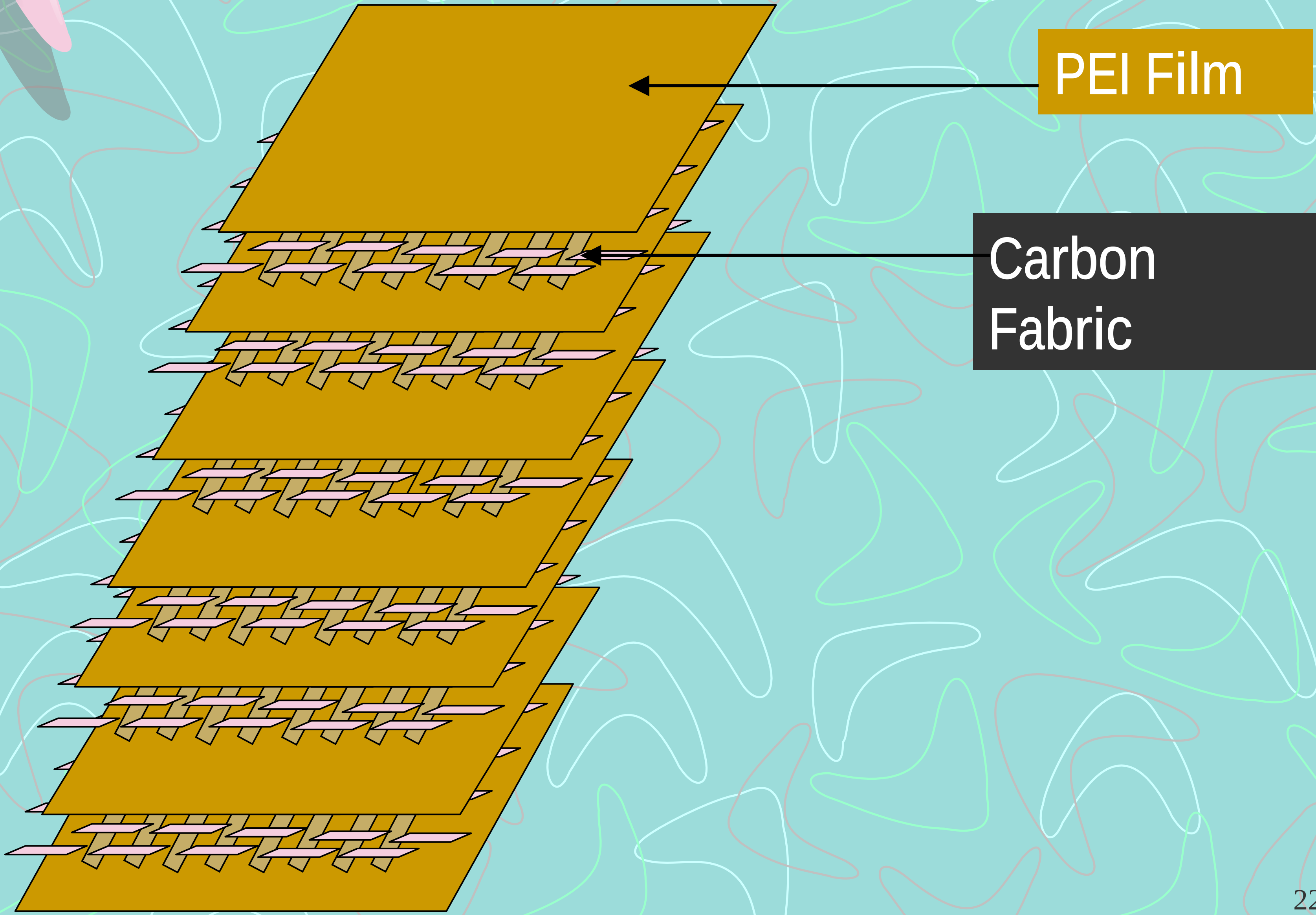
Fabric pieces of size

(280 mm x 2 60 mm) dipped in the solution of PEI in Dichloromethane (DCM) for 12 hrs.

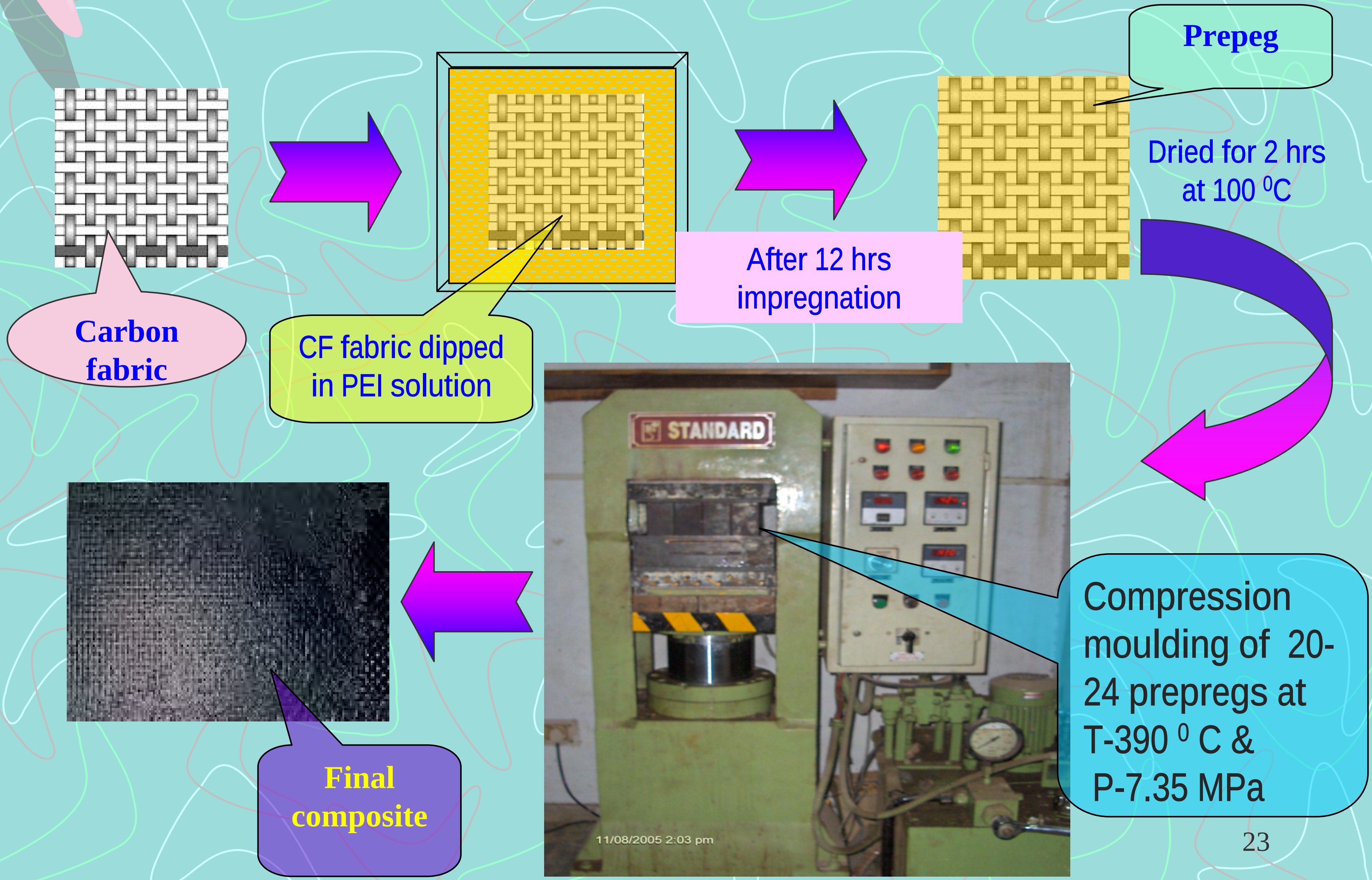


Prepregs of carbon fabric impregnated with PEI

Film Technique-alternate sequence of film & fabric piece



Schematic of fabrication of composites



3 series of composites

Series 1- Composites with varying amt of fabric with plain weave & Impregnation technique

Series 2- Composites with varying weave of fabric with 55vol % amt of fabric & Impregnation technique

Series 3- Composites with varying processing techniques- with 55% fabric & 3 weaves

Properties of Series 1- with varying amount of fabric (Vol%)-IP

Composites	PEI	IP_{85}	IP_{75}	IP_{65}	IP_{55}	IP_{40}
Density(g/cm^3) ASTM D 792	1.27	1.59	1.58	1.57	1.55	1.49
Contents of fabric, vol/wt %	-	85/90	75/80	65/72	55/65	40/50
Tensile strength(MPa) ASTM 638	105	562	691	697	535	330
Tensile mod.(GPa) ASTM 638	03	76	85	87	73	54
Elongation at break %)	60	0.44	0.32	0.25	0.54	0.87
Toughness (MPa) ASTM 638	-	2.5	1.8	1.4	3.8	3.0
Flex. strength (MPa)ASTM 790	150	367	1013	818	589	505
Flex mod. (MPa) ASTM 790	3.3	22	56	50	40	29
Inter laminar shear strength (ILSS) (MPa) ASTM 2344	-	33	45	54	49	35

- Significant increase in all properties except elongation
- IP_{65} showed the highest T.S &T.M and ILSS, while IP_{75} showed highest F.S & F.M
- Moderate amt. of CF (65-75 %) is recommended for best combination of properties.

Properties of Series 2- (varying weave of fabric)-Impreg-55% constant

Composites	PEI*	C_P	C_T	C_S
Density(g/cm^3) ASTM D 792	1.27	1.55	1.53	1.54
Contents of fabric, vol/wt % (+-2%)	-	55/65	55/65	55/65
Tensile strength (MPa) ASTM 638	105	535	*888*	575
Tensile modulus (GPa) ASTM 638	03	73	*106*	76
Elongation at break (%)ASTM 638	60	*0.54*	0.08	0.32
Toughness(MPa) ASTM 638	-	*3.8*	2.2	2.8
Flexural strength (MPa)ASTM 790	150	589	*951*	832
Flexural modulus (GPa) ASTM 790	3.3	40	*54*	46
Inter laminar shear strength (ILSS) (MPa) ASTM 2344	-	49	*66*	63

Designations-C_P ,C_T & C_S-Composites with plain, twill & satin weaves. Twill weave composite best in most of the properties except e & toughness. Satin weave second best except e & toughness.

Properties of Series 3 :Variation in processing technique

	Plain I tech.	Plain F tech.	Twill I tech.	Twill F tech.	Satin I tech.	Satin F tech.
Composites	IP_{55}	FP_{52}	IT_{55}	FT_{52}	IS_{55}	FS_{52}
Density(g/cm^3) ASTM D 792	1.55	1.53	1.53	1.52	1.54	1.54
Contents of fabric, volume/wt %	55/65	52/63	55/65	52/63	55/65	52/63
Tensile strength(MPa) ASTM 638	535	471	888	430	575	330
Tensile modulus (GPa) ASTM 638	73	73	106	69	76	53
Elongation at break (%)ASTM 638	0.54	0.58	0.08	0.81	0.32	0.87
Toughness (MPa) ASTM 638	3.8	2.2	2.2	2.4	2.8	2.6
Flexural strength (MPa)ASTM 790	589	270	951	245	832	333
Flexural modulus (MPa) ASTM 790	40	42	54	29	46	52
Inter laminar shear strength (ILSS) (MPa) ASTM 2344	49	18	66	12	63	15

Overall, Impregnation tech. proved far superior to film technique.

Tribo-evaluation under various wear situations (Adhesive & fretting)

Adhesive wear situations-

Bearings, bushes, gears, cams, slides etc

Fretting wear situations-

Where small oscillatory movement due to Intentional or unintentional vibrations takes place.

Examples- Bearings, gears, cams, slides ,bearing liners, spline couplings, gripped parts, flanges, seals, multilayered leaf springs, bolted/riveted/pinned joints etc.

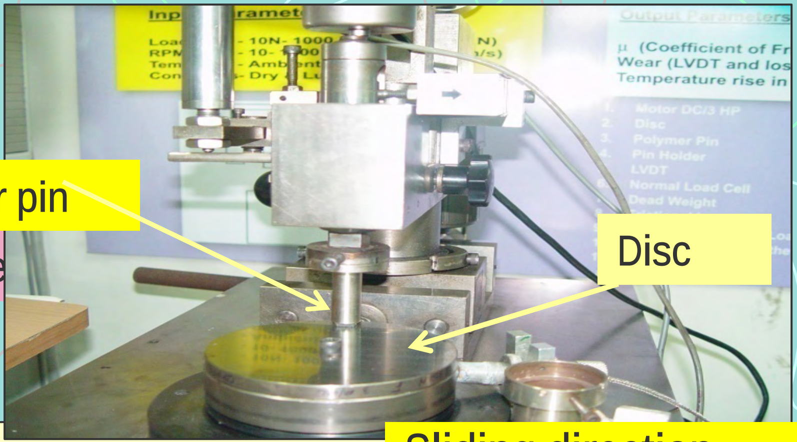
Sliding against smooth metal disc-Adhesive wear

Studies conducted on Single Pin on Disc machine in dry condition.

Polymer pin slid against disc (mild steel, Ra- 0.1-0.2 μm)

The selected operating parameters:

- Load: 200, 300, 400, 500, 600 N
- Velocity: 1m/s
- Sliding hrs-6 after uniform contact- wear loss measured after every 2 hrs. Average of last two readings reported as wear loss.
- Sliding distance in each interval-7.536 km
- Temperature 30°C & 90°C
- Fiber orientations-parallel & perpendicular to sliding direction



Pin On Disc Machine Fabricated by Magnum Engineers Bangalore, India

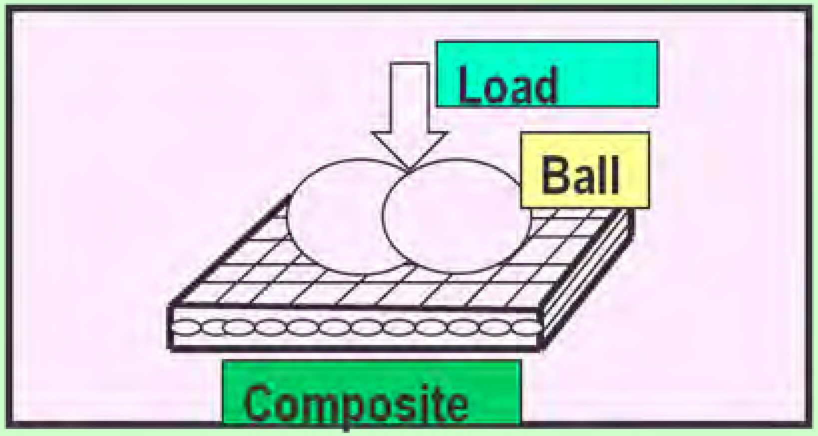
Low amplitude oscillating /Fretting wear

Tests done on SRV Optimol Tester,

Polished Cr steel ball 10 mm diameter oscillated against a composite plate (10mm x10mm x 4mm)

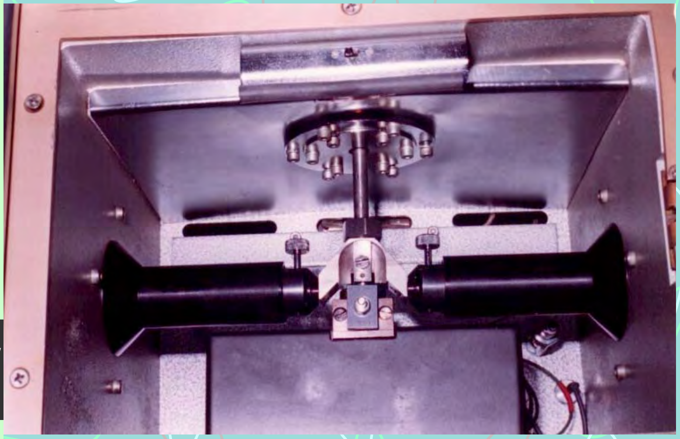
The operating parameters:

- Load: 100, 150, 200, 250 and 300N;
- Stroke length - 1 mm;
- Oscillating duration- 2 hrs;
- Oscillating frequency- 50 Hz,
- Temperature- 25°C
- Sliding distance- 720 m



Front view

Inner View



SRV Optimol

Results of Series 1- Adhesive wear mode

Observations:

- Significant increase in wear performance (almost by order of 3) and PV limit due to CF
- K_0 increased with increase in load due to increase in fiber damage.
- Too high & too less fibers –Not that good
- W_R (higher the better) / performance order

$IP_{65} > IP_{55} > IP_{75} > IP_{40} > IP_{85}$

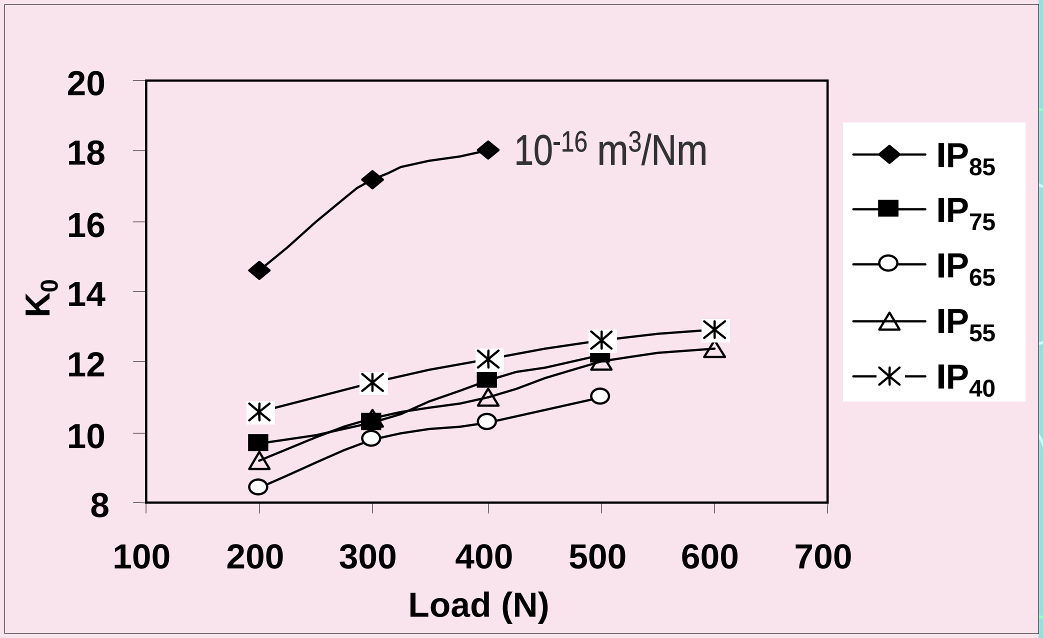
(identical order in ILSS)

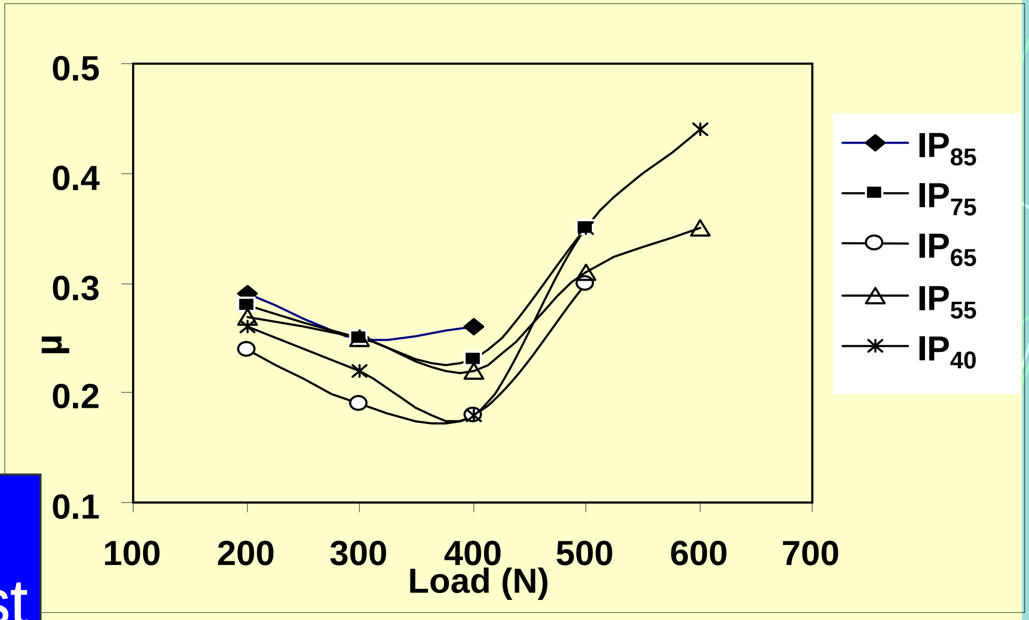
- Friction performance

(μ-lower the better)

$IP_{65} > IP_{40} > IP_{55} > IP_{75} > IP_{85}$

65 % range-best for μ & W_R & Strength while 85% proved poorest





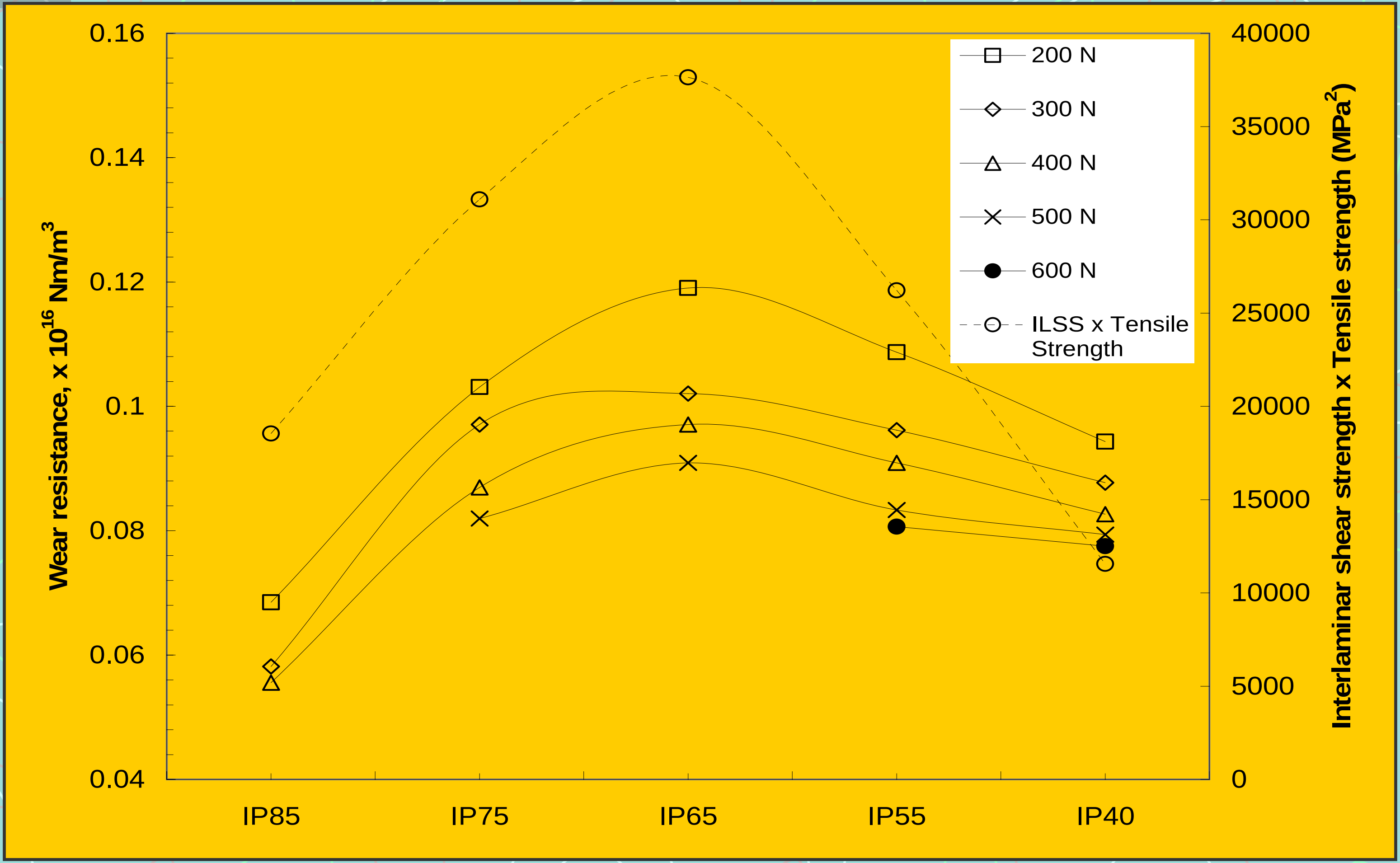
RWRE of Series I composites at various loads- Adhesive wear mode

The factor "relative wear resistance enhancement" was introduced to quantify the capability of composites to enhance the wear resistance as compared to the poorest. It was defined as;

Composites	IP_{40}	IP_{55}	IP_{65}	IP_{75}	IP_{85}
200N	1.37	1.58	1.74	1.50	1
300N	1.50	1.65	1.75	1.67	1
400N	1.48	1.63	1.76	1.56	1
500N	1	1.05	1.15	1.03	-
600N	1	1.04	-	-	-

$$\text{Relative wear resistance enhancement} = \frac{K_o \text{ of poorest composite}}{K_o \text{ of selected composite}}$$

Wear –property Correlation



Fairly good Correlation between sp wear rate (K_o) & product of T.S. & ILSS

Worn surfaces of best and poorest composites:

- Weave with warp & weft fibers visible
- Very smooth topography
- Gradual, longitudinal wearing of CF
- Least de-bonding of fibers and matrix after wearing under thermal & mech. stresses
- No peeling off of fibers supporting highest W_R of IP_{65}

- Weave with warp & weft fibers visible.
- Rough topography so peeling off of fibers
- Excessive fiber breakage & brittle fracture of matrix-Inadequate amt of matrix unable to support fibers ho wear preferentially.
- Less bonding between matrix and fibers supporting lowest W_R

Results of Series 1- Fretting wear mode

Observations:

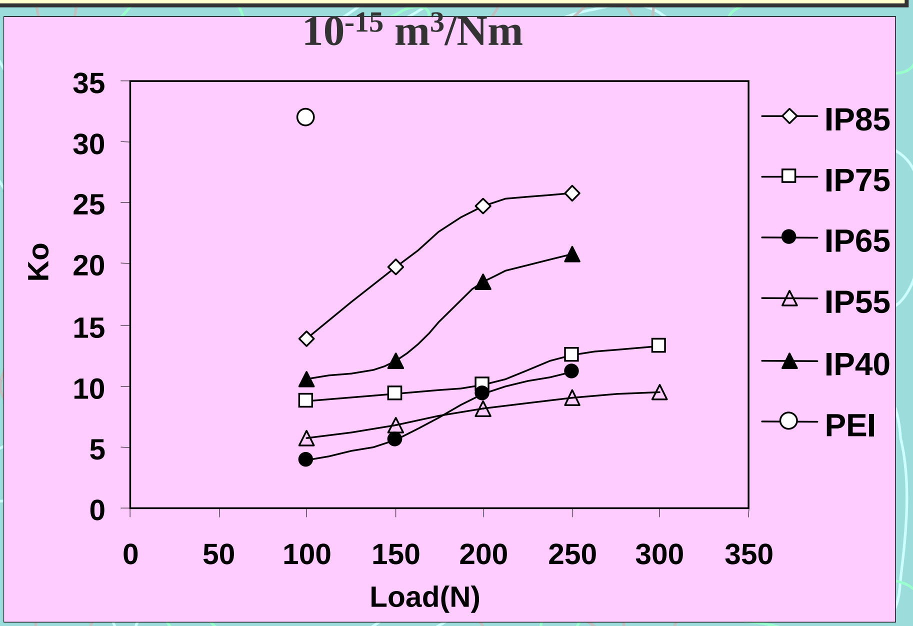
- Significant increase in wear resistance (almost 10 times) due to CF
- W_R of composites(higher the better)At 100N and 150N:

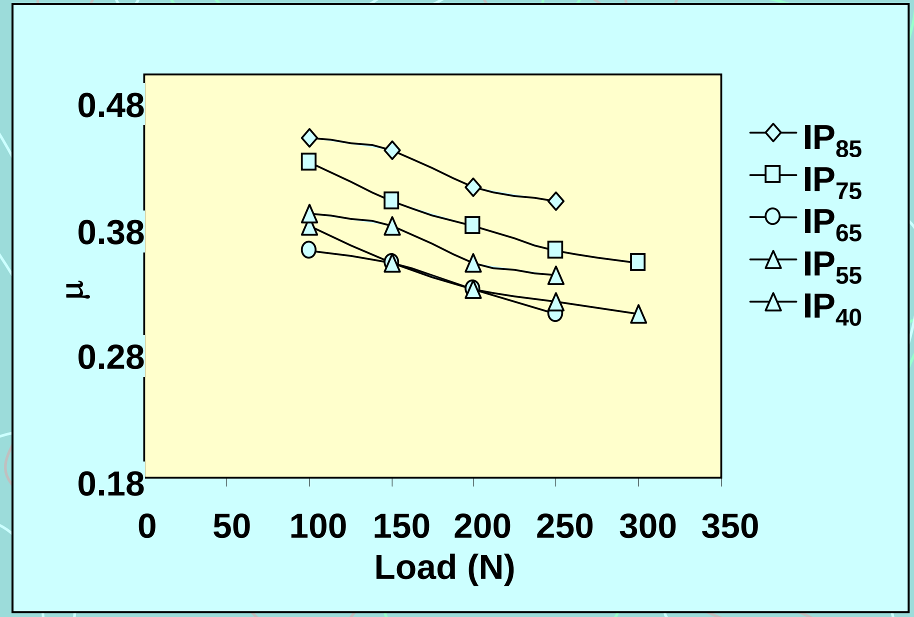
  $IP_{65} > IP_{55} > IP_{75} > IP_{40} > IP_{85}$
- Friction performance

(μ-lower the better)

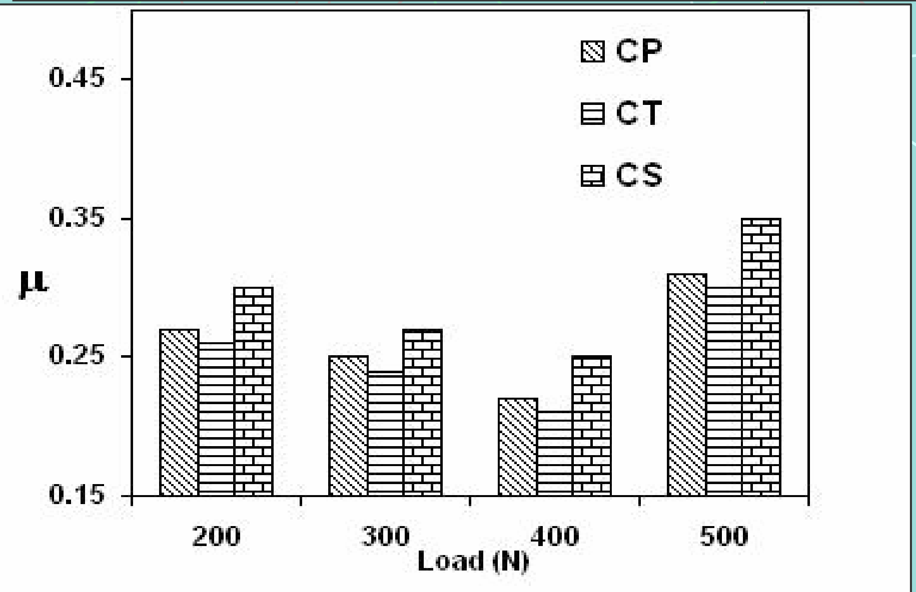
  $IP_{65} = IP_{55} > IP_{40} > IP_{75} > IP_{85}$

Overall, 65 & 55 vol % CF proved best & 85 vol % proved poorest.

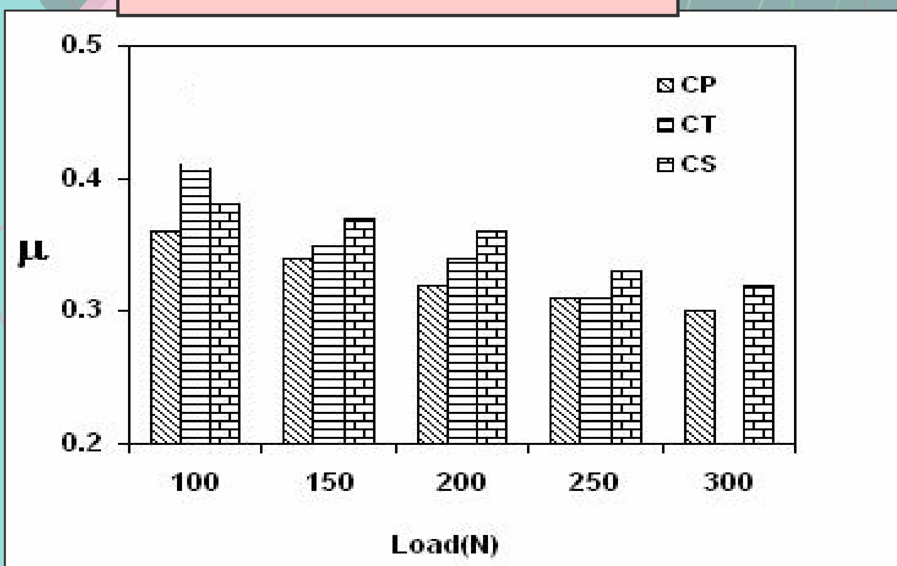




Results of Series 2- Adhesive & fretting wear modes



Adhesive wear mode



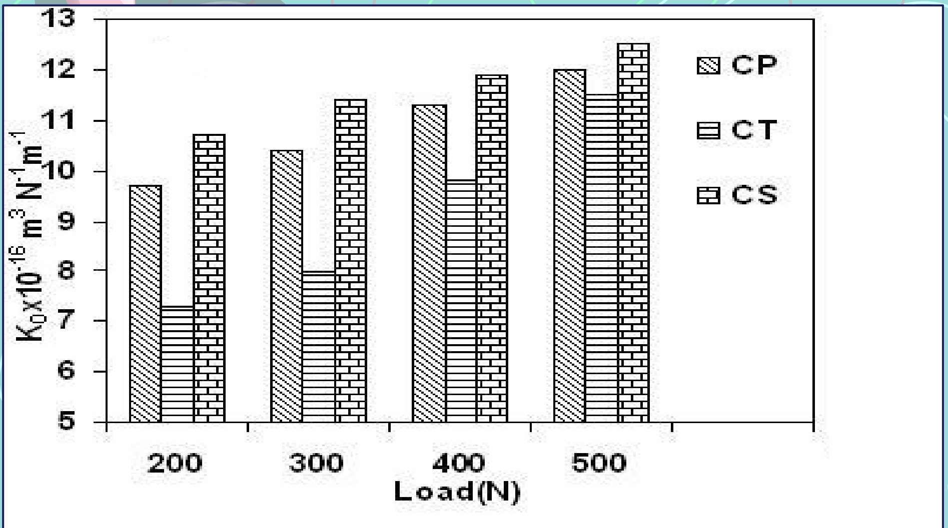
Fretting wear mode

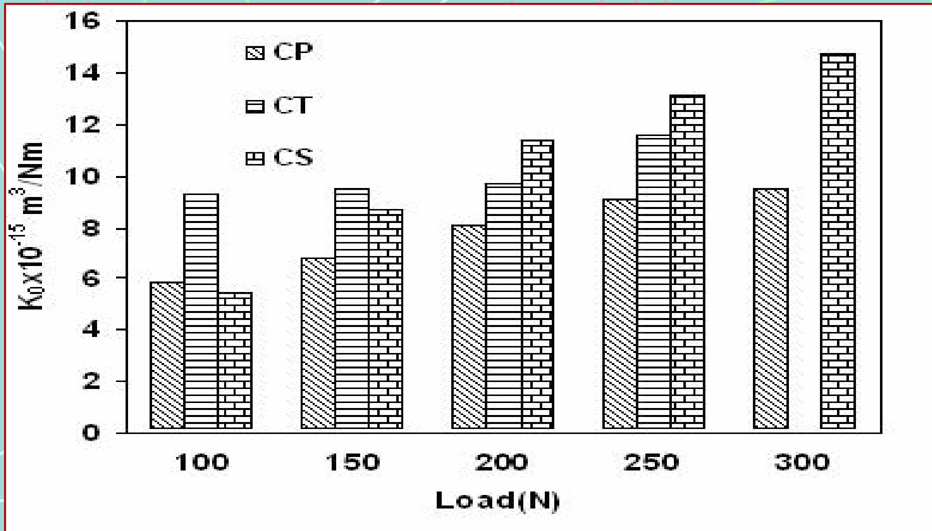
Salient features

- μ very high (approx. 1.1) when fibers normal to sliding plane-Hence studies conducted only when fabric was parallel to sliding plane
- Intra- comparison of μ not possible since loads, speeds are different.
- As load increased μ decreased in all modes. (exception- 500N-limiting load)
- μ in the range of 0.2-.3 under high PV range ---very good tribo-material- adhesive mode.

	Lowest μ	Highest μ	comment
Adhesive	CT-	CS	
Fretting	CP	CS	except 100 N –CT highest

Specific wear rate (K_o) under various loads & wear modes





adhesive wear

Fretting Wear

Salient observations

- Very low wear rate(x 10^{-16}) under high PV conditions- indicate very good tribo-material-in adhesive mode- Twill weave best; then plain
- Very low wear rate(x 10^{-15}) under high PV conditions- indicate very good tribo-material-in fretting mode- Plain best followed by twill
- Reinforcement deteriorated abrasive wear performance-Satin weave- best

Wear mode	K_o lowest	K_o highest	General comments
Adhesive	CT	CS	
Fretting	CP	CS	Except at low loads

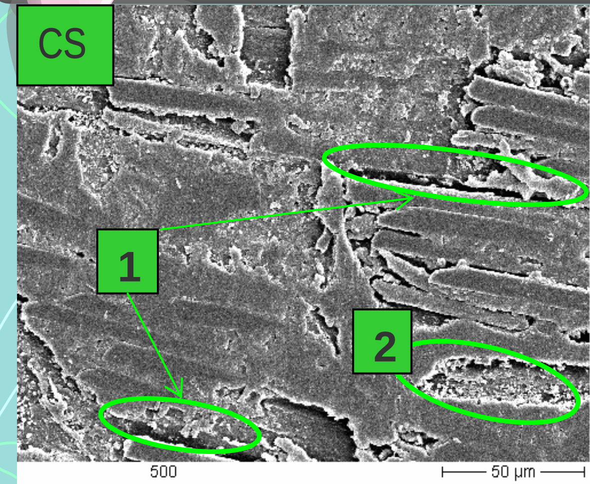
RWRE of Series II composites-Fretting wear mode

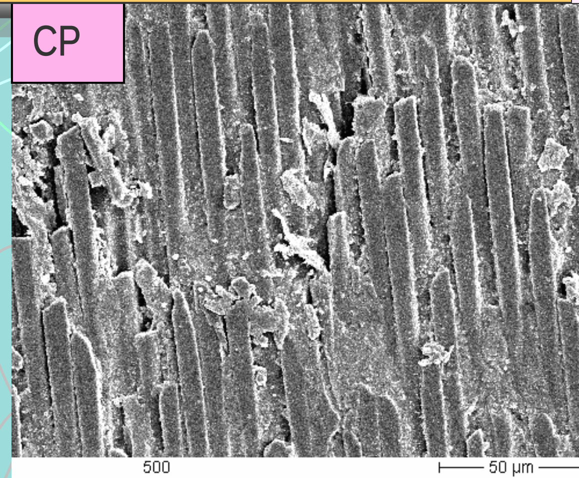
Composites	IP_{55}	IT_{55}	IS_{55}
200N	1.1	**1.46**	1
300N	1.09	**1.42**	1
400N	1.05	**1.21**	1
500N	1.04	**1.05**	1

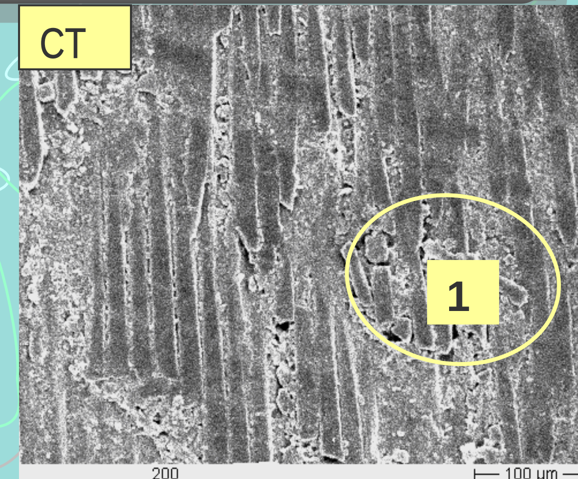
Twill weave composite best followed by plain weave composite

SEM (x400) Adhesive wear mode-(400 N)

$W_{resistance}$ CT>CP>>CS





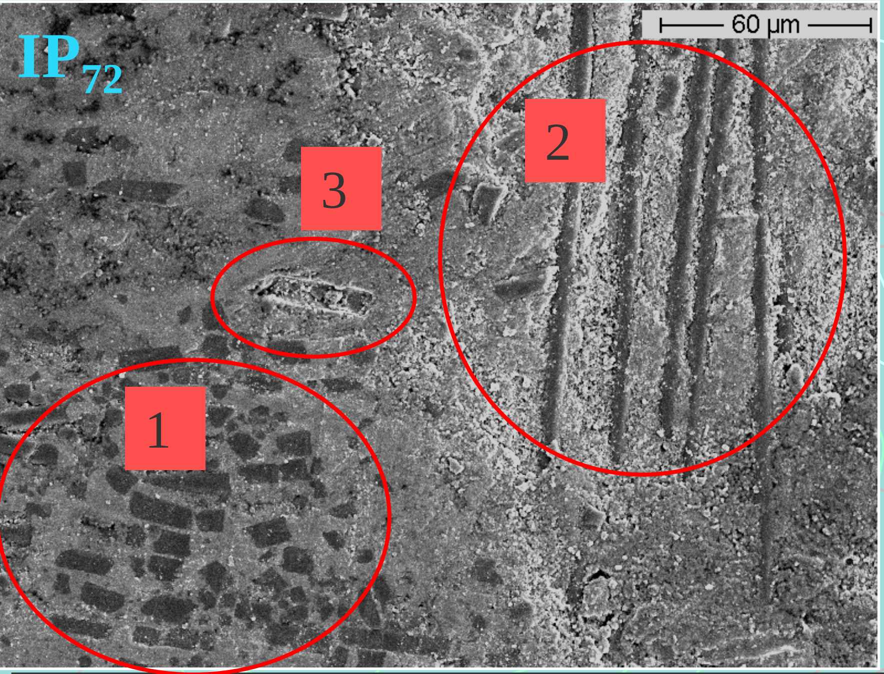


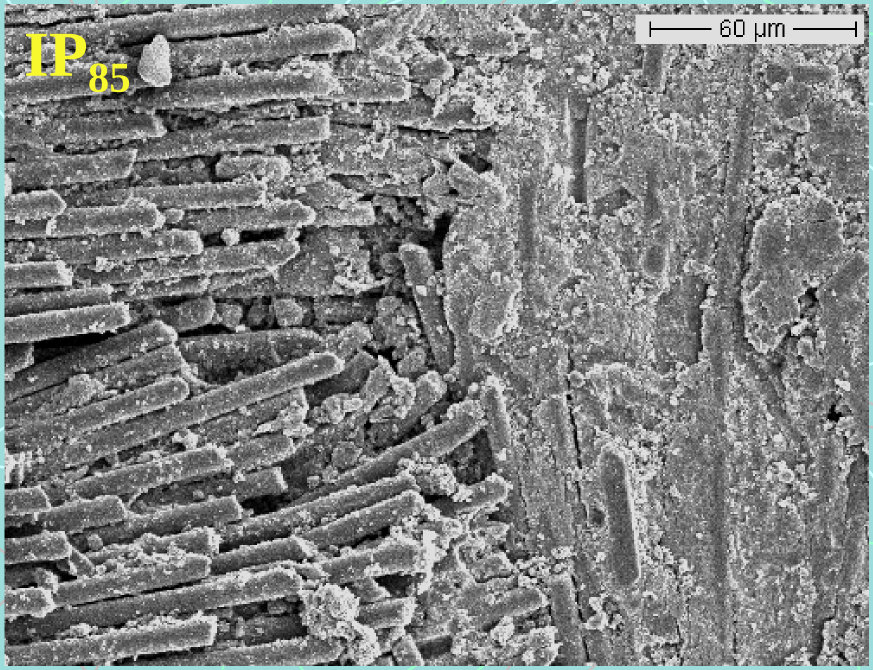
For C_S- showing higher damage to the fibers & matrix; lot of patches of back transferred resin, enhanced debonding in fiber-matrix interphase (1), cavities left after fiber consumption & filled with powdered fibers (2) – Supports highest wear

For C_p- showing higher damage to the fibers & matrix; lot of patches of back transferred resin, enhanced debonding in fiber-matrix interphase (1), cavities left after fiber consumption & filled with powdered fibers (2) Supports moderate wear

For C_T- Smoothest topography . (1) fiber damage and cutting but not pulverization. Longitudinal wearing of fibers-least debonding. Supports lowest wear

Worn surface analysis (fretting mode)





- Very smooth topography, excellent fiber-matrix bonding
- Preferential, gradual and longitudinal wearing of CF (marked 1 and 2); cavity filled with wear debris (marked as 3) supporting very good W_R

- Rough topography, loosely held fibers, fiber-matrix debonding.
- Excessive brittle fracture of CF support poor W_R

Conclusions:

Mech. strength properties

CF reinforcement enhanced

- Strength and modulus properties of PEI (almost by 700 % & 30,00 %)
- Optimum range of fabric necessary for this was 65-75 vol %
- Very high amt.(85%) of CF led to poor bonding of fiber and matrix, while very low amt.(40%) proved inadequate as a reinforcement.
- Twill weave proved best followed by plain and satin in I tech.
- Impregnation tech proved much superior to Film tech.

Inclusion of CF in PEI proved significantly beneficial from strength & modulus point of view.

Relative enhancement factor (REF) for composites

Composite	IP_{40}	IP_{55}	IP_{65}	IP_{75}	IP_{85}	IP_{55}	IT_{55}	IS_{55}	FP_{52}	FT_{52}	FS_{52}
T.S	3.14	5.09	6.64	6.58	5.35	5.09	8.45	5.47	4.48	4.09	3.14
T.M	18	24.33	29	28.33	25.33	24.33	35.33	25.33	24.33	23	17.66
F.S	3.36	3.92	5.45	6.75	2.45	3.92	6.34	5.55	1.8	1.63	2.22
F.M	8.78	12.12	15.1	16.96	6.6	12.12	16.36	13.93	12.72	8.78	15.75

Maximum enhancement in most of the properties with 65 % fabric, twill weave & impregnation technique

Tribo-properties: Weave & amt of fabric for best performing composite differed in two wear modes.

For fabrication of sliding parts (that are prone to adhesive wear) based on BD composites and thermoplastic polymer (PEI), with CF (PAN based high mod) following guidelines are recommended if best combination of physical (light-weight), mechanical and tribological properties is reqd.

- ✓ *amount of fabric in the composites - range of 55-65 vol%.*
- ✓ *impregnation technique better than film technique.*
- ✓ *twill weave best to attain high W_{R}, low μ and high strength*.
- ✓ Orientation of high mod CF should be parallel to the sliding plane.

Tribo-composite for **fretting wear applications** where vibrations are unavoidable and the operating conditions are severe (very high PV and unlubricated), is to be tailored from thermoplastic materials with a combination of properties such as easy processability and advantages associated with BD reinforcements, along with best combination of physical (light-weight), mechanical and tribological properties, following guidelines could be useful.

- A thermoplastic PEI as a binder
- PAN based high modulus carbon fabric as a reinforcement
- Plain weave (or next twill weave)
- Moderate amt of CF, preferably in the range of 55-65 % (vol)
- Impregnation technique
- Orientation o fabric- parallel to sliding plane

- These composites thus proved to have excellent potential for dry bearing materials for severe operating conditions- (Very high PV values, very high wear resistance & low coefficient of friction).
- Significant potential for construction material in aircrafts/spacecrafts.
- The studies offers guidelines for selection of weave of fabric, its orientation with respect to loading direction, its amount and processing technique for tailoring the composite for desired set of properties & tribo-performance in selected wearing conditions.


Thanks