A combination of technical expertise and business savvy

- Over 15 years of experience in innovation and industry: Cookson, Institute for Surface Chemistry (YKI), Electrolux, BASF, Hybrid Plastics & Phantom Plastics
- Recognized expert in plastics, filled plastics, fillers, dispersants, coupling agents, formulation, stabilization and more
- Serial innovator: many inventions, 13 patents & 3 Innocentive cash awards
- Papers, articles, book chapters, presentations & workshops
- Fellow of the Royal Society of Chemistry & Chartered Chemist
- Winner of Frost & Sullivan award 2009 and R&D 100 Award 2009
- Voted top plastics expert world-wide out of over 10 000 peers
- President of Phantom Plastics providing consultancy and training services to the plastics industry
Phantom Plastics™ capabilities

Many faceted approach to deliver solutions

- Analysis
- Marketing
- Problem Solving
- Global Networking
- Breakthrough Innovation
A foundation for working with polymers and composites

- Introduction to fillers and polymers
- Common fillers and their characteristic properties
- Common polymers and how structure affects their properties
- How fillers affect polymer processing and properties of polymers
- Cheat sheet summarizing how all these factors influence the properties of the composite
- Misconceptions about filled plastics
- Further reading, consultants, web resources
Reasons to use fillers

Innumerable different reasons to use fillers

- Raise heat resistance
- Increase stiffness
- Increase strength
- Reduce shrinkage
- Improve dimensional stability
- Reduce flammability
- Modify flow
- Increase lubricity
- Decrease permeability
- Increase degradability
- Improve processability
- Reduce creep
- Change electrical properties
- Modify specific gravity
- Improve abrasion resistance
- Improve impact strength
- Improve thermal conductivity
- Improve moisture resistance
- Increase adhesion
- Appearance, opacity, gloss

Phantom Plastics™
Basic polymer mechanical properties

Polymer behavior depends on testing speed and temperature

Stress or Force (MPa) vs Strain or elongation (%)

- Brittle failure
- Yield
- Ductile failure
- Increasing temperature or lower testing speed
- Break or ultimate
- Energy to break
Impact test methodology

The notch provides crack initiation and helps consistency

Notched Izod

Notched Charpy
Fillers improve modulus

High aspect ratio is best

- Glass Fibre
- Mineral Fibre
- Mica
- Talc
- CaCO3
- Wood Fibre
- Nanoclay
- Wollastonite

Filler Volume (%) vs. Modulus (GPa)
Anisotropic fillers can improve yield strength

High aspect ratio is best
Aspect ratio & impact resistance

Anisotropic fillers worse for impact resistance

Filler in PP copolymer
- Talc
- Kaolin
- Calcium Carbonate
- Mica

Falling Weight Impact Resistance (J)

Aspect ratio

Courtesy of Imerys
Influence of glass fibre on HDT/B

Fillers very effective but only in semi-crystalline polymers

Phantom Plastics™
## Cheat sheet

### How to modify the properties of composites

<table>
<thead>
<tr>
<th>Property</th>
<th>Isotropic</th>
<th>Platy</th>
<th>Fibres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus</td>
<td>↑</td>
<td>↑↑</td>
<td>↑↑↑</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>—</td>
<td>↑</td>
<td>↑↑</td>
</tr>
<tr>
<td>HDT in amorphous polymer</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>HDT in semi x-line polymer</td>
<td>↑</td>
<td>↑↑</td>
<td>↑↑↑</td>
</tr>
<tr>
<td>Impact resistance</td>
<td>↑ or ↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Elongation to break</td>
<td>↓</td>
<td>↓↓</td>
<td>↓↓↓</td>
</tr>
<tr>
<td>Permeability</td>
<td>↓</td>
<td>↓↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

- Adding dispersant improves impact resistance, elongation, gloss & flow but modulus & yield strength unchanged
- Adding coupling agent will improve yield strength but not modulus, flow may worsen
- Adding impact modifier particles will improve impact resistance but will lower modulus, yield strength and flow
- Isotropic fillers work in all three directions equally
- Platy fillers are very good in two directions and fair in the other
- Fibers are very good in one direction and fair in the other two
Fallacies

Some common misconceptions

- MFI is a good indicator flow
- Coupling agents always couple
- Coupling increases modulus
- Anisotropic fillers are better
- Properties depend on weight % filler
- Filler reduce the specific heat capacity of polymers
- Nano-composites are new
- Impact strength is a valid term
- Impact resistance is an intrinsic property
- Notched impact resistance is most meaningful
- Fillers function is just to reduce cost
Dispersants improve impact resistance: coupling agents for strength

<table>
<thead>
<tr>
<th>Surface treatment types</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dispersant</strong></td>
</tr>
<tr>
<td>A --- B</td>
</tr>
<tr>
<td>Anchor --- Buffer</td>
</tr>
<tr>
<td><strong>Coupling Agent</strong></td>
</tr>
<tr>
<td>A --- B --- C</td>
</tr>
<tr>
<td>Anchor --- Buffer --- Couplant</td>
</tr>
</tbody>
</table>
### Anchor group filler specificity

Succinic anhydride is a very effective anchor group

<table>
<thead>
<tr>
<th>Filler Type</th>
<th>Best Dispersant</th>
<th>2nd Best</th>
<th>3rd Best</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Carbonate</td>
<td>Succinic anhydride</td>
<td>Carboxylic acid</td>
<td>Primary amine</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Sulfonic acid</td>
<td>Carboxylic acid</td>
<td>Succinic anhydride</td>
</tr>
<tr>
<td>Magnesium Hydroxide</td>
<td>Succinic anhydride</td>
<td>Trichlorosilane</td>
<td>Carboxylic acid</td>
</tr>
<tr>
<td>Mica</td>
<td>Primary amine</td>
<td>Trichlorosilane</td>
<td>Sulfonic acid</td>
</tr>
<tr>
<td>Talc</td>
<td>Trichlorosilane</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Silica</td>
<td>Trichlorosilane</td>
<td>Sulfonic acid</td>
<td>Succinic anhydride</td>
</tr>
<tr>
<td>Wollastonite</td>
<td>Primary amine</td>
<td>Succinic anhydride</td>
<td>Carboxylic acid</td>
</tr>
<tr>
<td>Titanium dioxide</td>
<td>Succinic anhydride</td>
<td>Carboxylic acid</td>
<td>Trichlorosilane</td>
</tr>
</tbody>
</table>
Coupling agents and modulus

Coupling and modulus – bonding does not affect modulus

Polycarb S – surface treated
Polycarb - untreated

Flexural modulus (MPa)

Filler volume %

Courtesy of Imerys
Nanopolymers

Coupling and yield strength – coupling agents raise yield strength

B. Pukánsky in Polypropylene Structure, blends & composites vol 3

Graph showing the tensile yield strength (MPa) as a function of filler volume percentage. The graph compares untreated (poor adhesion), stearic acid treated (poorer adhesion), and maleated PP (good adhesion) samples.
Effect of flow

Fibres and flakes align to give high tensile strength and modulus

Direction of flow
Fillers improve modulus

High aspect ratio is best

**Graph**

- **Title**: Fillers improve modulus
- **Subtitle**: High aspect ratio is best
- **Axes**:
  - Y-axis: Modulus (GPa)
  - X-axis: Filler Volume (%)
- **Data Points**:
  - Glass Fibre
  - Mineral Fibre
  - Mica
  - Talc
  - CaCO3
  - Wood Fibre
  - Nanoclay
  - Wollastonite

**Legend**:
- Glass Fibre: cyan dots
- Mineral Fibre: green dots
- Mica: orange dots
- Talc: black dots
- CaCO3: purple dots
- Wood Fibre: brown dots
- Nanoclay: magenta dots
- Wollastonite: blue dots
Anisotropic fillers can improve yield strength

High aspect ratio is best

![Graph showing the relationship between filler volume and yield stress for different fillers: Glass Fibre, Mineral Fibre, Mica, Talc, CaCO3, Wood Fibre, Nanoclay, and Wollastonite. The graph indicates that the yield stress increases with increasing filler volume, and high aspect ratio fillers like Glass Fibre and Mineral Fibre show the most significant improvement.]
Fillers give weld lines – weak points that cause failure
Fillers and weld line strength

More anisotropic fillers give lower weld line strength

![Graph showing yield strength comparison between different plastics with and without weld lines](image)

- **ABS**
- **PP Unfilled**
- **PP (50% CaCO3)**
- **PP (30% GF)**

Yield Strength (Mpa)

Courtesy of Electrolux
Always plot properties versus volume % filler to get straight lines!

\[
\rho_c = \frac{\rho_f \times \rho_p}{\rho_p m_f + \rho_f \times (1-m_f)}
\]

- \(\rho_c\): density of the composite
- \(\rho_f\): density of the filler
- \(\rho_p\): density of the polymer
- \(m_f\): weight fraction of filler (between 0 & 1)
Density versus weight % air as a filler

1 weight % air halves the mass of the material
### Volume specific heat capacity of polymers

Average is 2.1 kJ / litre.K

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Melt Density (g/cm³)</th>
<th>Mass Specific Heat of melt (kJ/kg.K)</th>
<th>Volume Specific Heat (kJ/litre.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PES</td>
<td>1.48</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>PVC-U</td>
<td>1.15</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>PET</td>
<td>1.15</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.88</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1.01</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>SAN</td>
<td>0.92</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>PMMA</td>
<td>1.01</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>PPO</td>
<td>0.92</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>ABS</td>
<td>0.89</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>PBT</td>
<td>1.12</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Acetal / POM</td>
<td>1.22</td>
<td>2.5</td>
<td>3.1</td>
</tr>
<tr>
<td>PA 6</td>
<td>0.95</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>PA 6,6</td>
<td>0.97</td>
<td>2.7</td>
<td>2.6</td>
</tr>
<tr>
<td>PP</td>
<td>0.85</td>
<td>2.7</td>
<td>2.3</td>
</tr>
<tr>
<td>LDPE</td>
<td>0.79</td>
<td>3.2</td>
<td>2.5</td>
</tr>
<tr>
<td>HDPE</td>
<td>0.81</td>
<td>3.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Aramid Fibers*</td>
<td>1.45</td>
<td>1.42</td>
<td>2.1</td>
</tr>
<tr>
<td>Average</td>
<td>---</td>
<td>---</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Source: Polypropylene The Definitive User’s Guide and Databook except *Handbook of Fillers
### Volume specific heat capacity of mineral and metallic fillers

Average is 2.1 kJ / litre.K

<table>
<thead>
<tr>
<th>Mineral or Metal</th>
<th>Density (g cm(^{-3}))</th>
<th>Mass Specific Heat (kJ/kg.K)</th>
<th>Volume Specific Heat (kJ/litre.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN (hexagonal)</td>
<td>2.25</td>
<td>0.794</td>
<td>1.8</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.65</td>
<td>0.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Silver</td>
<td>10.5</td>
<td>0.188</td>
<td>2.0</td>
</tr>
<tr>
<td>Talc</td>
<td>2.75</td>
<td>0.82</td>
<td>2.3</td>
</tr>
<tr>
<td>Tungsten</td>
<td>19.35</td>
<td>0.088</td>
<td>1.7</td>
</tr>
<tr>
<td>Beryllium Oxide</td>
<td>2.85</td>
<td>1.03</td>
<td>2.9</td>
</tr>
<tr>
<td>Average</td>
<td>---</td>
<td>---</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Source: Handbook of Fillers
Impact resistance is an energy (area under the curve) **not** a strength.

**Penetration test**

Standard velocity $4.4 \text{ ms}^{-1}$

$J = \text{total energy}$

Force (Newtons)

Deflection (mm)
Take impact resistance results in context and with a grain of salt.

VINCENT, P. I.  

PC 3mm 8.6J, 6mm 1.6J so suppliers only show thin specimen results.
Impact test methodology

The notch provides crack initiation and helps consistency

Notched Izod

Notched Charpy
## CaCO₃ – particle size & cost

Prices must be compared on a per unit volume basis

<table>
<thead>
<tr>
<th>Cost Euro / ton</th>
<th>Cost Euro / litre</th>
<th>Size CaCO₃ d₅₀ microns</th>
<th>Approximate Polymer prices € / L</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.27</td>
<td>~ 2</td>
<td>PP 0.68</td>
</tr>
<tr>
<td>200</td>
<td>0.54</td>
<td>~ 1</td>
<td>PE 0.74</td>
</tr>
<tr>
<td>300</td>
<td>0.81</td>
<td>~ 0.5</td>
<td>PS 0.84</td>
</tr>
<tr>
<td>400</td>
<td>1.08</td>
<td>~ 0.3</td>
<td>HIPS 0.85</td>
</tr>
<tr>
<td>500</td>
<td>1.62</td>
<td>~ 0.1</td>
<td>PVC 0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PET 1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>ABS 1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nylon 2.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PC 2.8</td>
</tr>
</tbody>
</table>

**Phantom Plastics™**
Filled polymers property profile

Fair impact resistance, higher stiffness, retained strength, lower cost

Impact modifier (volume %)

<table>
<thead>
<tr>
<th>Impact resistance</th>
<th>Tensile strength</th>
<th>Modulus</th>
<th>Melt viscosity</th>
<th>Materials cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

Impact modifier (volume %)
Some excellent resources I use every day

- Functional Fillers for Plastics, Marino Xanthos (Ed.), Wiley-VCH, 2005
- [www.specialchem.com](http://www.specialchem.com) great resource for polymers, additives and more
- [www.matweb.com](http://www.matweb.com) free searcheable polymer properties data
- [www.eng-tips.com](http://www.eng-tips.com) free polymer & composites advice
- [www.phantomplastics.com](http://www.phantomplastics.com) consultancy services – new materials, additives, training and problem solving
Thanks!