Graphene and Composite Materials

The Graphene Council

Research, Development and Application

This presentation will;

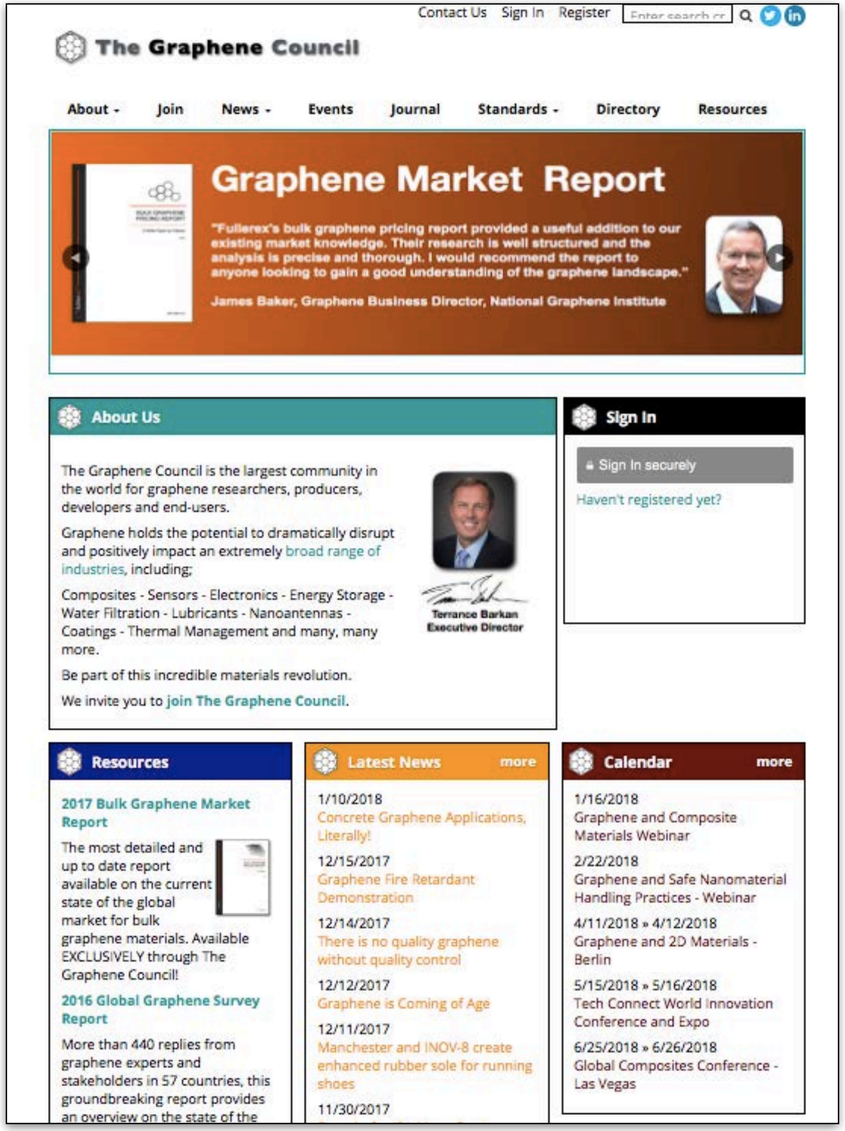
- **Understand the different types and grades of graphene materials**
- **Understand the range of plastics, polymers, and epoxies that graphene may be suitable for to enhance their properties**
- **Understand what you need to know about how to select and handle the right material for your target application**

Graphene and Composite Materials

About The Graphene Council

The Graphene Council is;

- **The largest community in the world for graphene researchers, developers, producers and other stakeholders.**
- **Formal members of the ISO/ANSI/IEC Graphene Standards development working groups.**
- **Produce original information, content and reports on the state of the graphene industry and takes a lead in facilitating commercialization through education and networking.**

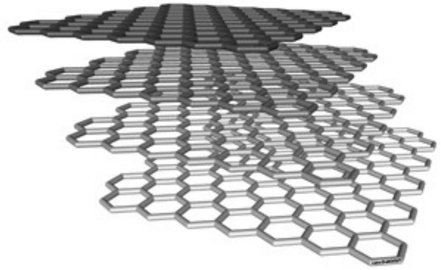


Types of Graphene Materials Used in Composites

Forms of Graphene

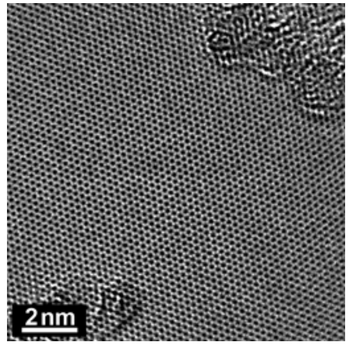
Definitions

- Graphene is a two dimensional (i.e. one atom thick) planar sheet of sp^2-bonded carbon atoms in a dense honeycomb shaped crystal lattice.



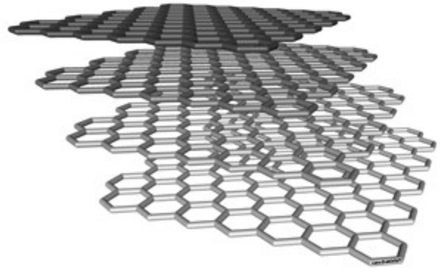
- Graphene has extraordinary material properties including ultimate tensile strength of 130 gigapascals, electron mobility of 15,000 cm2·V−1·s−1, thermal conductivity between 2000–4000 W m−1K−1 and optical transparency of 97.7%. (Eric Pop, 2012) (Sheehy DE, 2009)

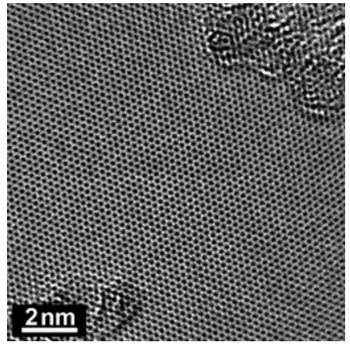
- ISO/TS 80004-13:2017(en) Nanotechnologies — Vocabulary — Part 13: Graphene and related two-dimensional (2D) materials. Recognizes material up to and including 10 carbon layers as “graphene”.



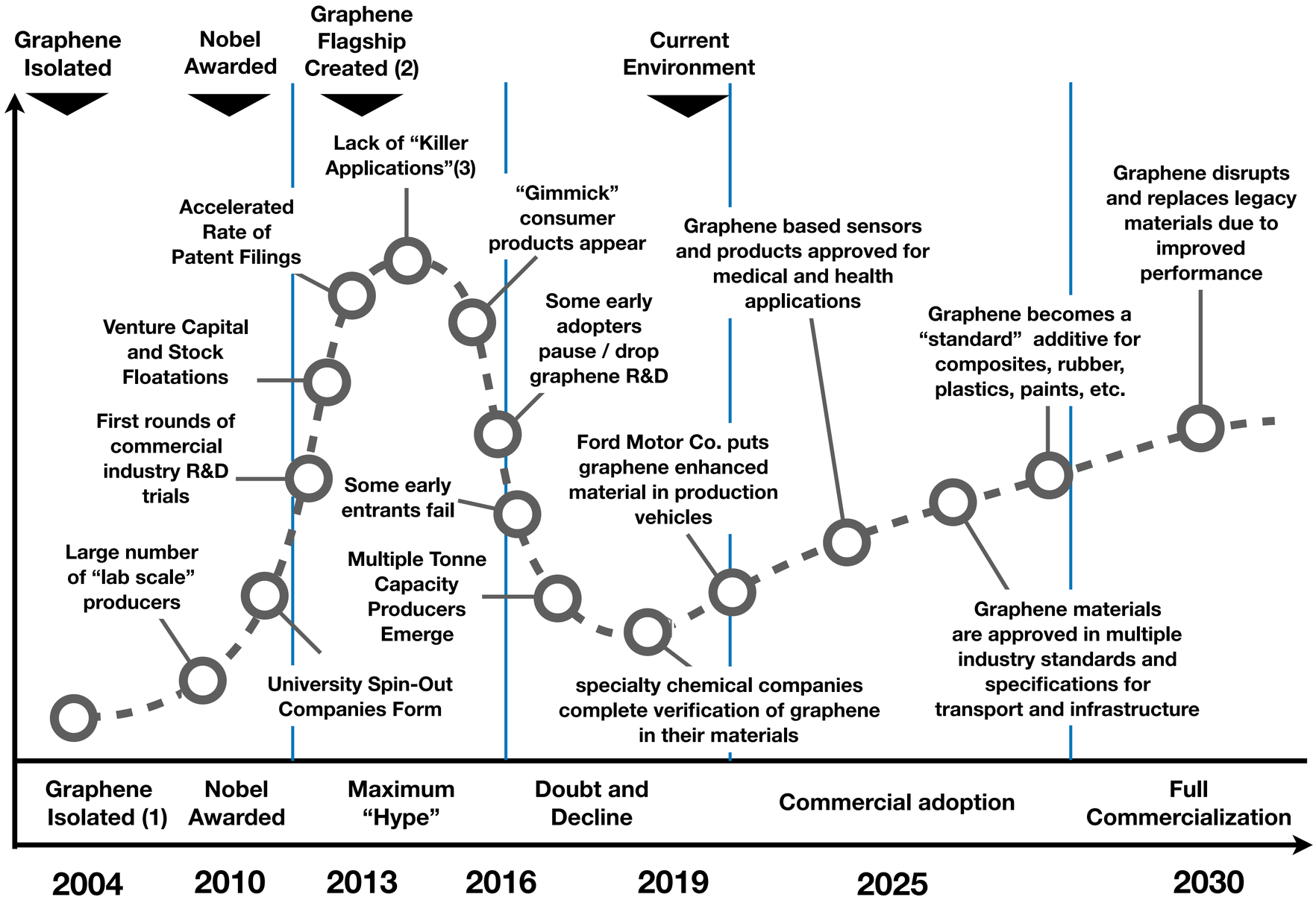
Superlatives of Graphene

- thinnest imaginable material
- strongest material ever measured (theoretical limit)
- stiffest known material (stiffer than diamond)
- most stretchable crystal (up to 20% elastically)
- record thermal conductivity (outperforming diamond)
- highest current density at room temperature
- highest intrinsic mobility (100 times more than in Si)
- conducts electricity in the limit of no electrons
- lightest charge carriers (zero rest mass)
- impermeable (contains He atoms)





The Graphene “Hype Cycle”



1) “Electric Field Effect in Atomically Thin Carbon Films”, K. S. Novoselov et. al, Science, Vol. 306, Issue 5696, pp. 666-669 (2004)

2) The Graphene Flagship is a 10 year, Euro 1 billion program sponsored by the European Union.

3) Focus was on the development of never before possible applications made entirely out of graphene, such as a “space elevator”

Note:

The evolution of a “hype cycle” is not uniform and is a gradual process where stages often overlap.

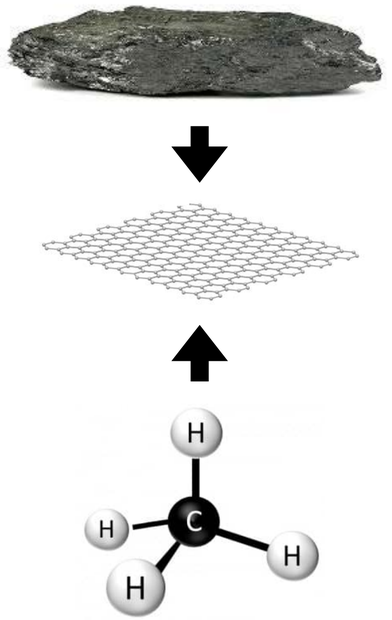
The dates indicated are based on our observations of the global graphene research and production environment.

Some geographic markets and industry sectors move faster than others and are therefore at different stages accordingly.

Source: The Graphene Council

Production Methods

- Graphene production methods can be classified broadly as “Top Down” and “Bottom Up”.
- “Top Down” methods start with a feedstock material such as graphite and through various methods (physical, electrical, chemical, etc.) exfoliate individual layers of carbon.
- “Bottom Up” methods start with a carbon feedstock such as methane gas that under controlled conditions (such as Chemical Vapor Deposition-CVD) is deposited on a substrate material (such as copper) in single or multiple layers.



Graphene Materials

- **A wide range of materials in the commercial market are currently referred to as “graphene”.**

Number of Carbon Layers	Description
1	CVD, Mono-layer or “Pristine” Graphene
1 - 3	Very Few Layer Graphene (vFLG)
2 - 5	Few Layer Graphene (FLG)
2 - 10	Multi-Layer Graphene (MLG)
> 10	Exfoliated graphite or “Graphene nanoplatelets” (GNP)

Forms of Graphene

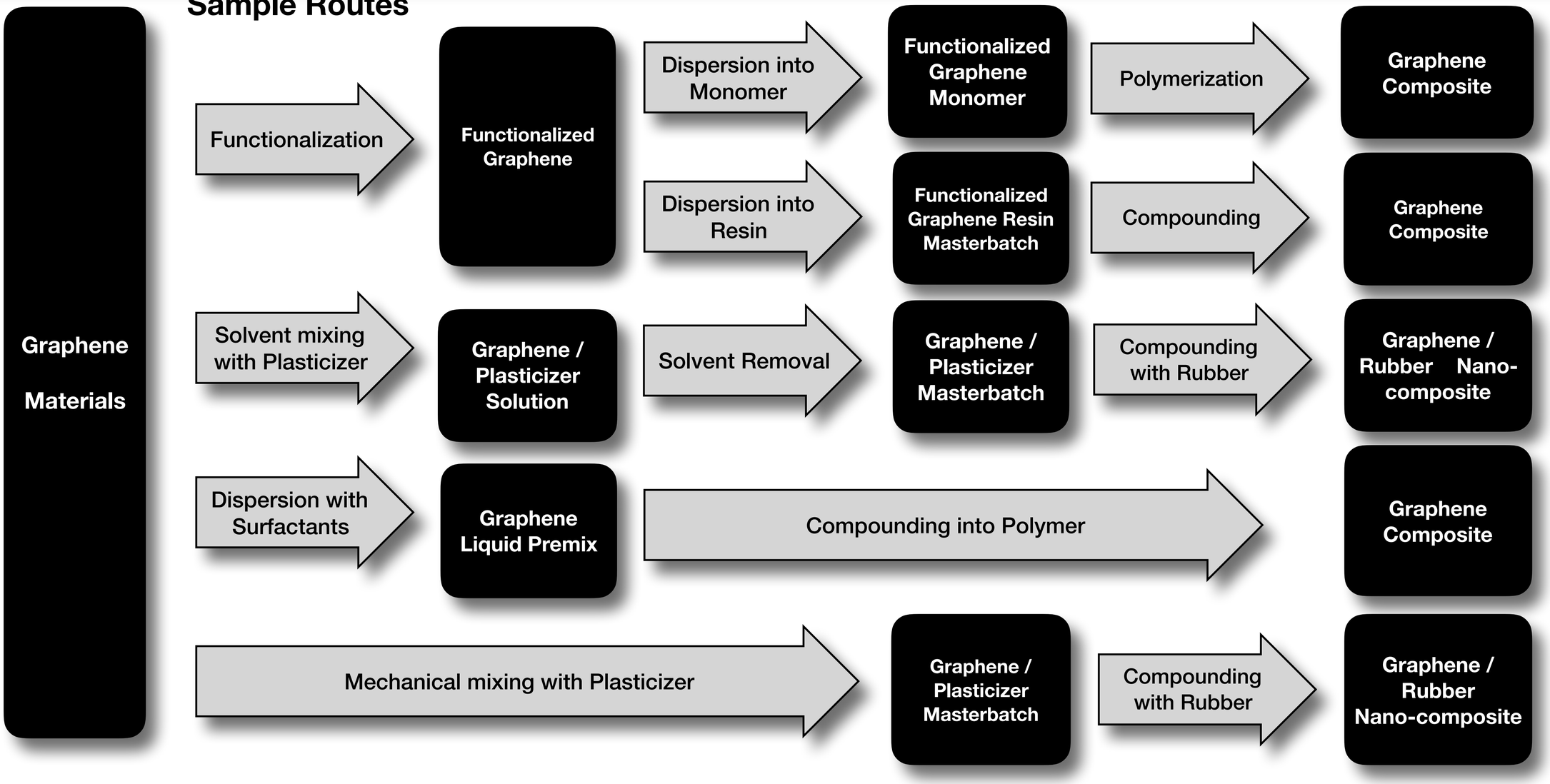
Type	Carbon Layers	Properties/Applications	Typical commercial cost ($/KG)	Commercially available
Epitaxial CVD	1-2	Conductive/almost Transparent/ High end electronics	Up to $500,000/m²	CVD systems- Scale up (on wafers) Cost!
FLG	3-10	Conductor/flexible/very high surface area/Sensors	$100-2,000	Yes- consistency? Processibility?
MLG	11-20	Composites/Inks and coatings/ Lubricants/Printing	$50-1,500	Yes
GO	various	Insulator? Amorphous Hydrophillic-dispersions Defects and voids. Cement	$50-2,000	In Part- still evolving but growing
Graphite used in GNP production	50+	Lubricants/Refactories/brakes/ Engineering materials	$1-20	Established for 150 years Approx. 1m tonnes pa

Forms of Graphene

- **In addition to the number of carbon layers, additional characteristics define the material.**
  - **Graphene Oxide (GO) - a compound of carbon, oxygen and hydrogen (typically approx. 65% carbon / 35% oxygen by weight).**
  - **Reduced Graphene Oxide (rGO) - Graphene Oxide in which removes much of the oxygen content resulting in approximately 95% carbon by weight.**
  - **Graphene Powder, Solution or Paste - Graphene material can be prepared in various physical forms including as a dry (usually black) powder, in solution (e.g. water or alcohol) or in a paste form (often as a dull reddish brown color).**
  - **Graphene Nano Platelets (GNPs) - GNPs typically have thickness of between 1 nm to 3 nm and lateral dimensions ranging from approximately 100 nm to 100 µm.**
  - **Functionalized Graphene - Chemical functionalization (adding specific elements to the surface or edges of the graphene) is important in many applications where untreated graphene would be difficult or impossible to work with.**

Graphene Dispersion Routes

Sample Routes



Sources: Fullerex Ltd. and Cealtech Inc.

Graphene “Quality”

There is widespread confusion about the definition of “Quality Graphene”.

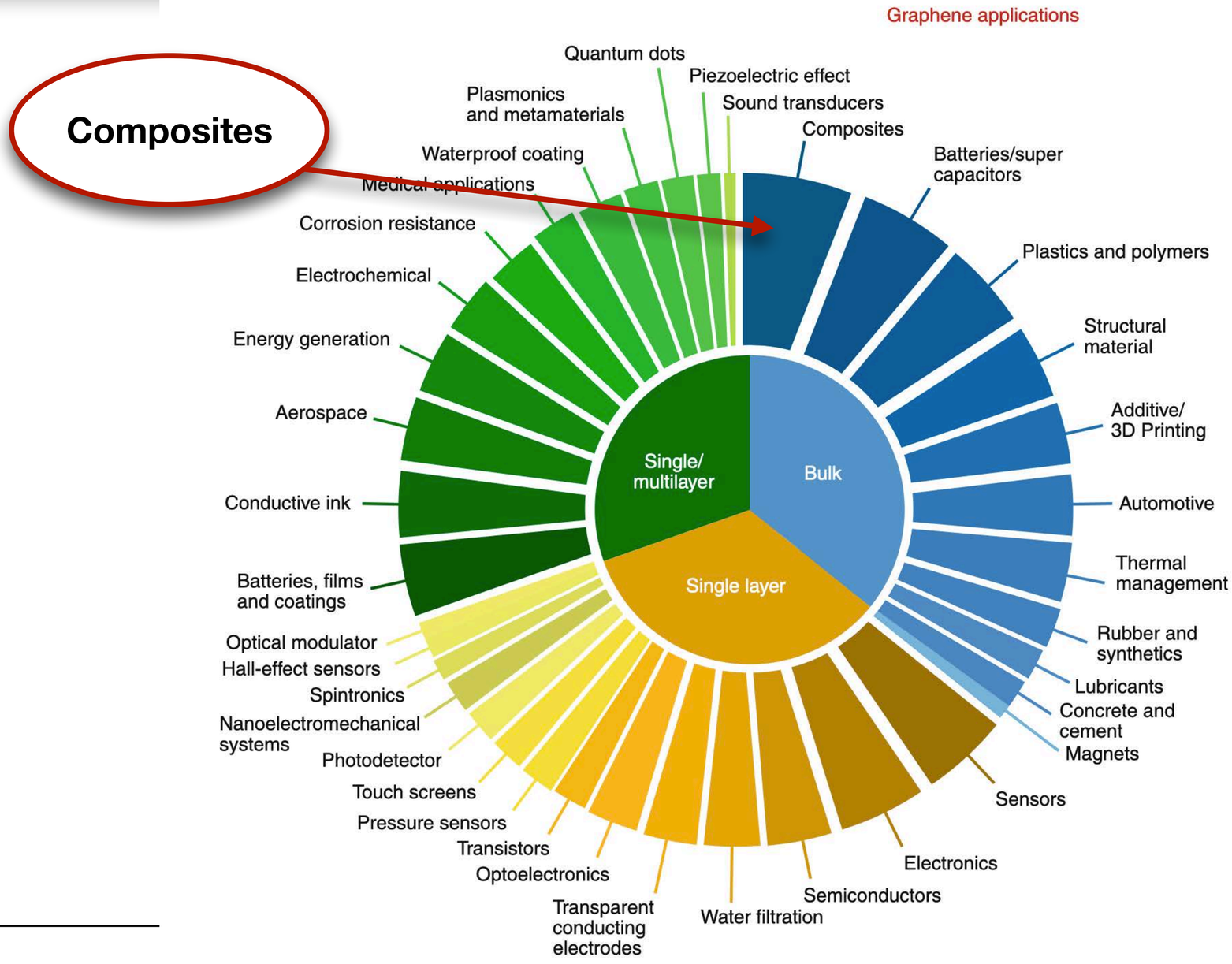
- **Material that is not suitable for one application may be ideal for another.**
- **Graphene “defects” may actually enhance the efficacy of the material for a particular application.**
- **There is no such thing as a reference material for graphene at this time.**
- **Because load factors can be quite low (less than 1% by weight or even 0.01’s%), the price of the material is not the most significant factor when selecting source material.**
- **The primary factor is in selecting a trusted and competent supplier of the material that understands your application areas.**
- **The physical morphology of the material has a significant impact on efficacy (layer count and lateral flake size from sub 1µm to <100µm.**

Examples of Graphene Enhanced Composites and Applications

Graphene Applications

Of the more than 40 major applications areas for graphene, ‘Composites’ form the largest single application area.

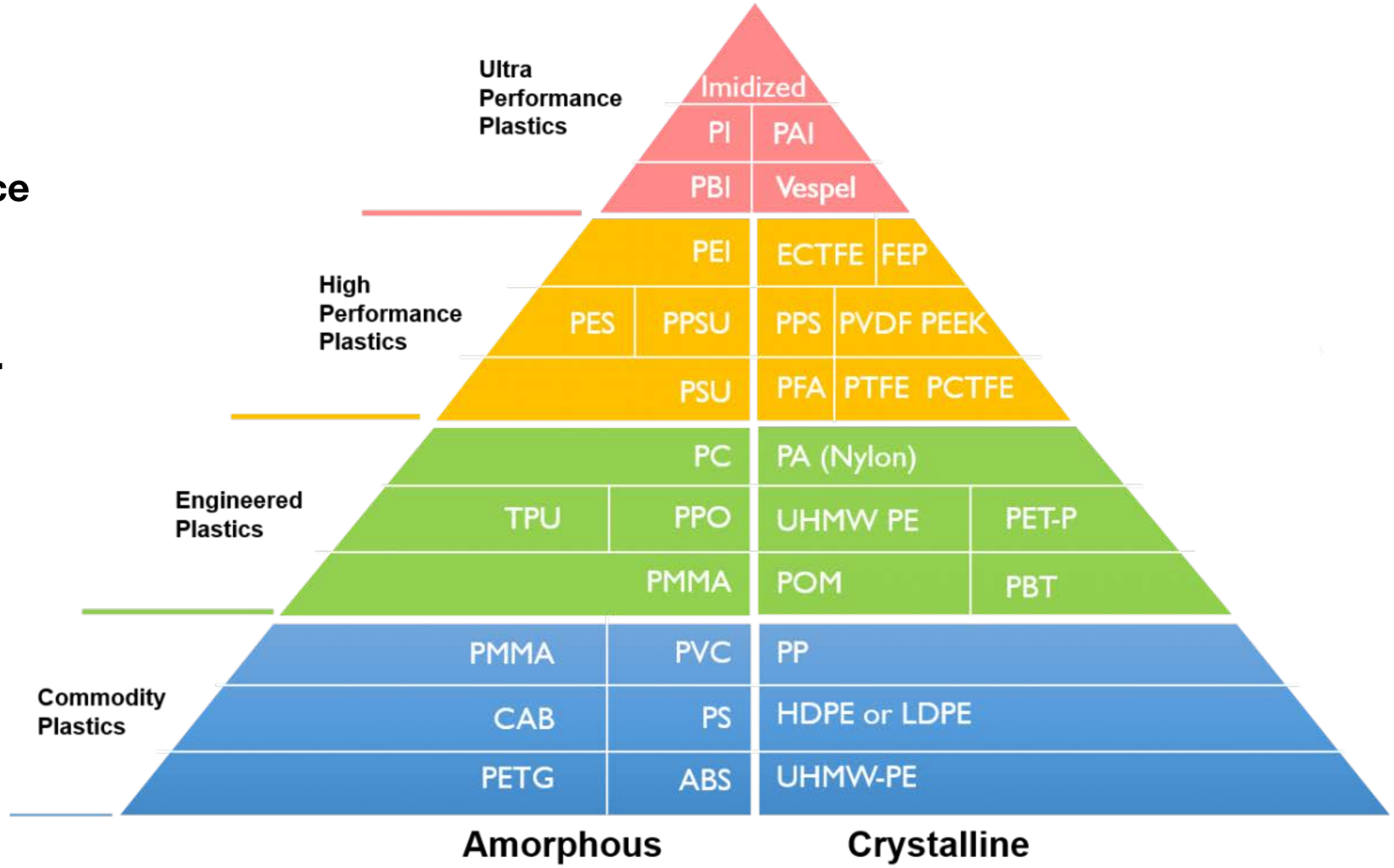
The type of graphene most suited for composites will be “bulk” or multi-layer materials



Application Areas

Plastics

Graphene can be used to enhance performance in a wide range of polymer systems including, Thermosets and Thermoplastics.



Composite Applications

Graphene is used to enhance performance in a wide range of applications;

- **Aerospace**
- **Automotive**
- **Sports Equipment**
- **Marine**
- **Rubber**
- **Plastics**
- **3D printing**
- **Coatings and Barriers**
- **Polymers and Epoxies**
- **Carbon Fibre Reinforced Polymer (CFRP)**
- **Glass Fibre Reinforced Polymer (GFRP)**

Material Performance Characteristics

Performance Improvement Targets

Graphene is used to provide enhanced performance metrics;

- **Electrical Conductivity**
- **Thermal Managment**
- **UV Protection**
- **Longer Wear**
- **Anti-Static**
- **Weight Reduction**
- **Robustness, Stiffness**
- **Mechanical Reinforcement**
- **Impact Performance**
- **Flexibility**
- **Barrier Properties**
- **Sensors (Enabling)**
- **Barrier Properties**
- **Fire Retardation**

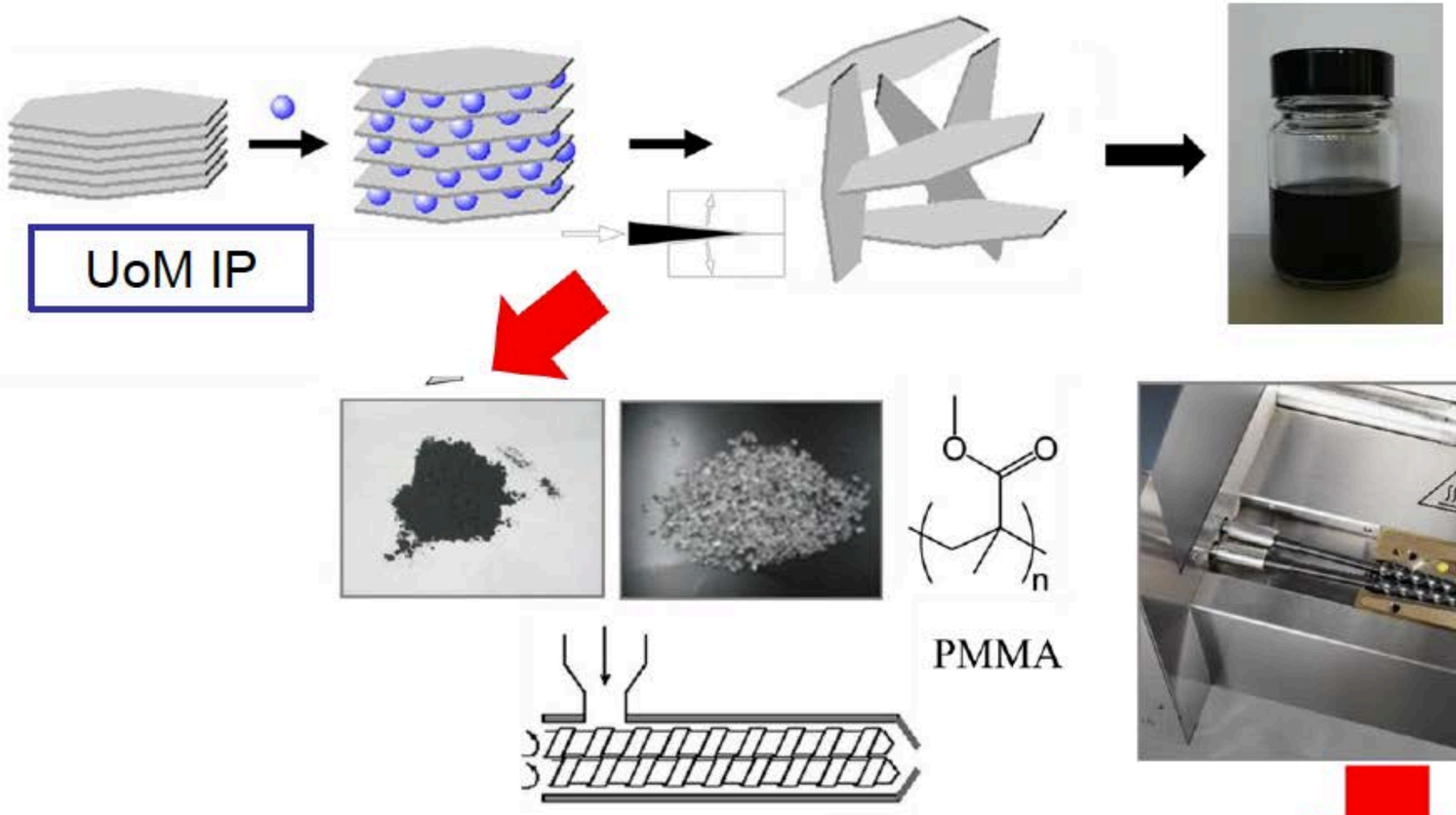
MANCHESTER 1824
The University of Manchester
National Graphene Institute

Injection moulded PMMA–graphene composites

Graphene can be added to Thermoplastics with a twin screw extruder.

Lateral flake size of the graphene can have an impact on viscosity.

<5 µm flakes have little impact while >20 µm flakes will increase viscosity



- Melt processing of composites using standard compounding and injection moulding.

Application Case Study:

Automotive

XGPU **Foams**

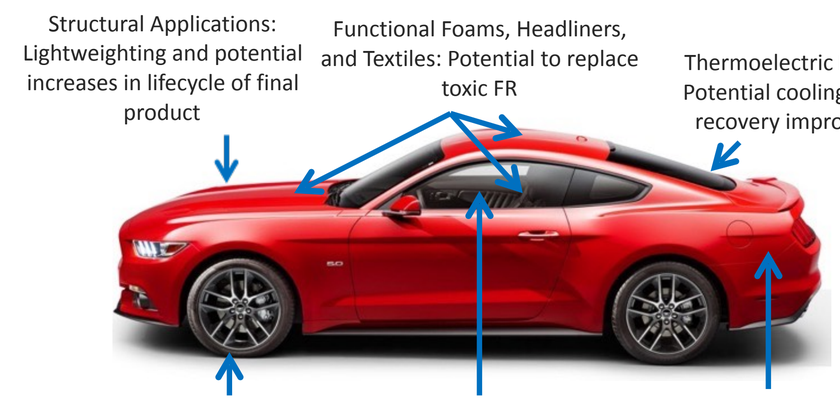
Multiple performance improvements in PU foam application, enabled by the addition of xGnP®

xGSciences™ + Ford Go Further

Graphene-Enhanced PU Foams

- **Improved compression strength by 20%**
- **Improved NVH (noise & vibration) by 17%**
- **Improved heat deflection temperature by 30%**

Parts in Production



Application Case Study:

Sporting Goods

xGnP® + Elastomers

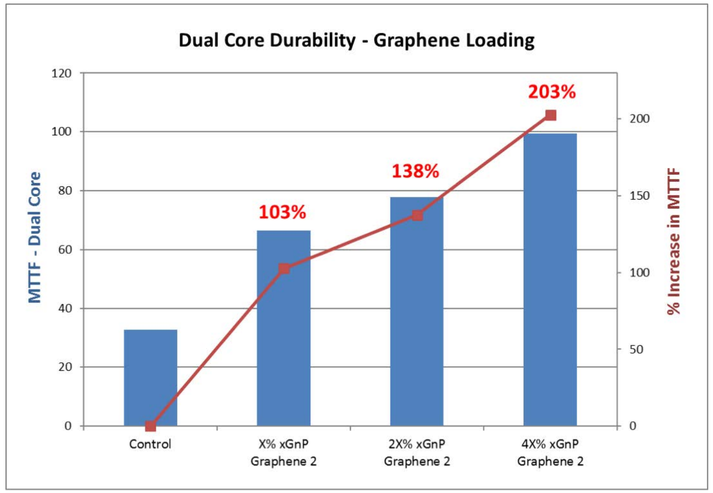
Performance enhancements via graphene-enabled innovation

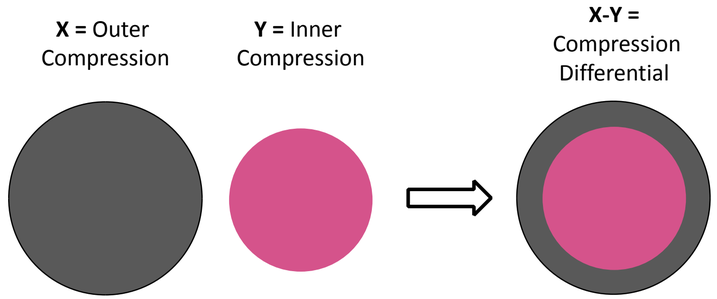
xGSciences™ + Callaway

Graphene-Enhanced Golf Balls

More Distance Off the Tee ⬣ Increased Spin Control ⬣ Retain Soft Feel

- Graphene-infused Dual SoftFast Core maximizes compression energy while minimizing driver-spin and promoting high launch for longer distance
- Higher MTTF with the graphene infused Dual Core design





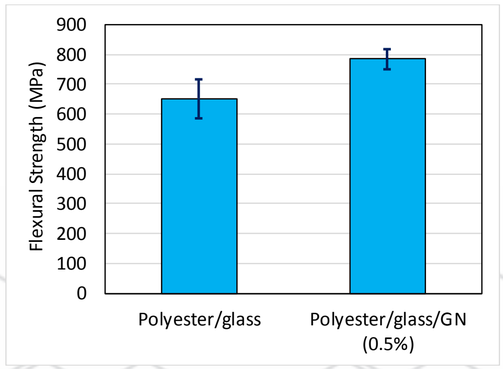
- Dual Core design
- Soft inner + firm outer = better spin performance

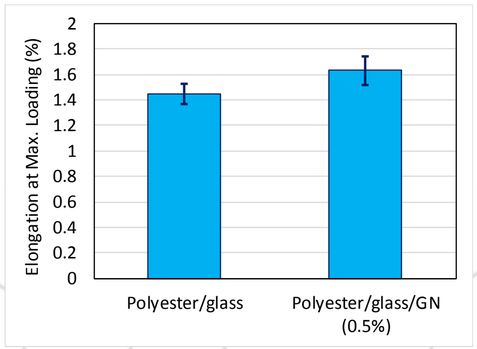
Graphene Pultrusion: Case Study

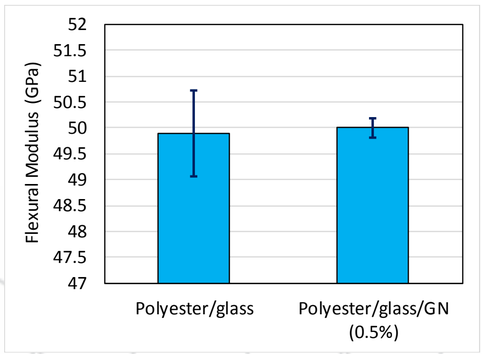
Improvements: >20% in flexural strength and >12% in the elongation only by addition of **0.5% graphene** to polyester/glass rods.

ASTM D790

	Flexural Strength (Mpa)	SD	Elongation at max Loading (%)	SD	Modulus (GPa)	SD
Polyester/glass	651.22	66.06	1.45	0.08	49.9	0.83
Polyester/glass/GN (0.5%)	784.24	34.96	1.63	0.11	50	0.19







polyester/glass

polyester/glass/GN (0.5 wt%)

Industrial Volume

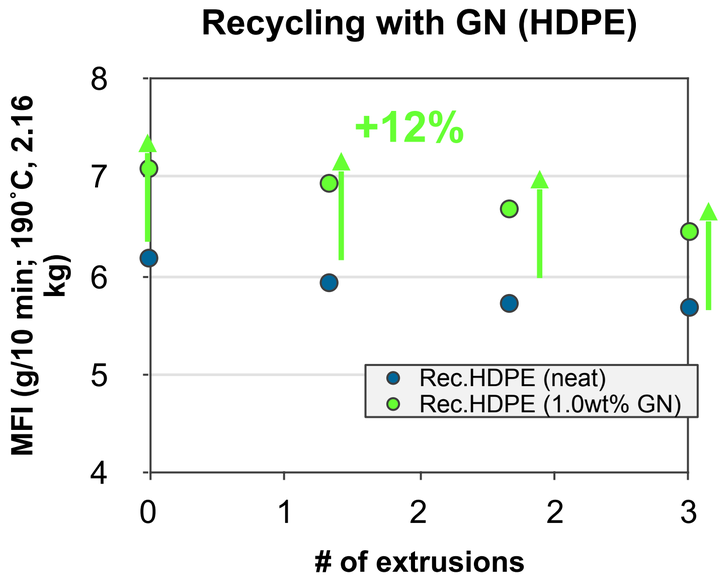
Proprietary Technology

Low-Cost

Recycled Materials: Processability

Melt Flow Index - MFI

- ✓ GrapheneBlack3X® acts as a processing aid increasing the MFI of the recycled polyethylene.
- ✓ At very low contents, there is an improvement of about 12% helping to control molecular weight and viscosity.
- ✓ GrapheneBlack3X® attenuates the decline of processability resulting from repeated processing cycles.



Industrial Volume

Proprietary Technology

Low-Cost

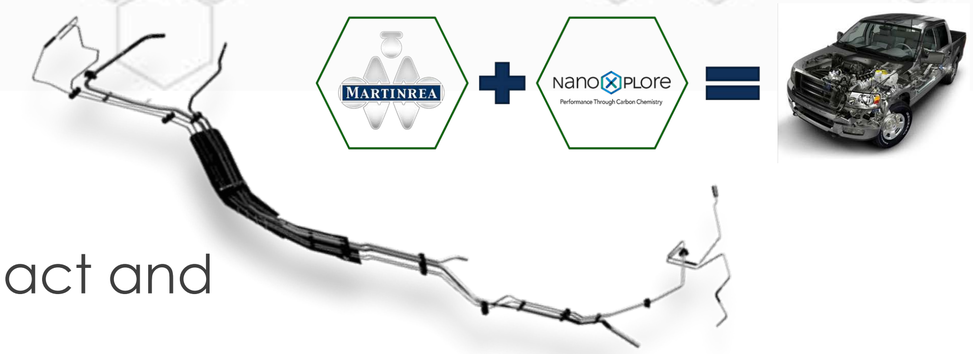
Processability

Extend Lifetime

Graphene Enhanced Coatings

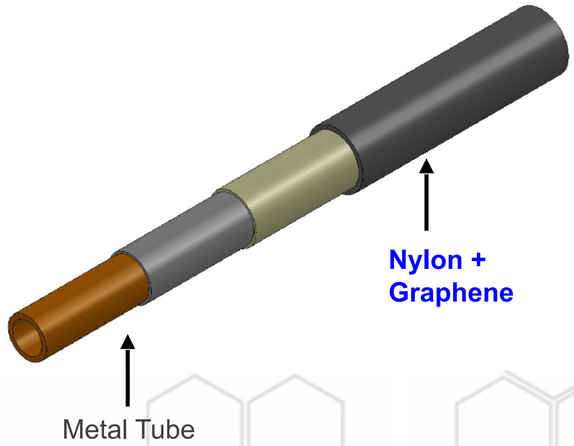
Abrasion Resistance:

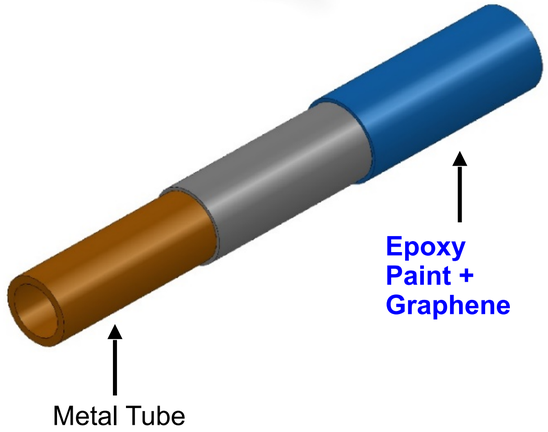
- Nylon / Graphene
- Epoxy / Graphene
- Improve robustness of coating to resist impact and abrasion conditions



Corrosion Protection:

- Improving the barrier to salt water solution penetration to base steel
- Prolonged component life





Industrial Volume

Proprietary Technology

Low-Cost

Graphene Application Examples

Aecom uses graphene by Versarien to 3D print an arch support structure

Aecom has produced a graphene arch using additive manufacturing techniques intended to reduce the time and cost of installing digital signalling systems and transform the digitization of transport networks.

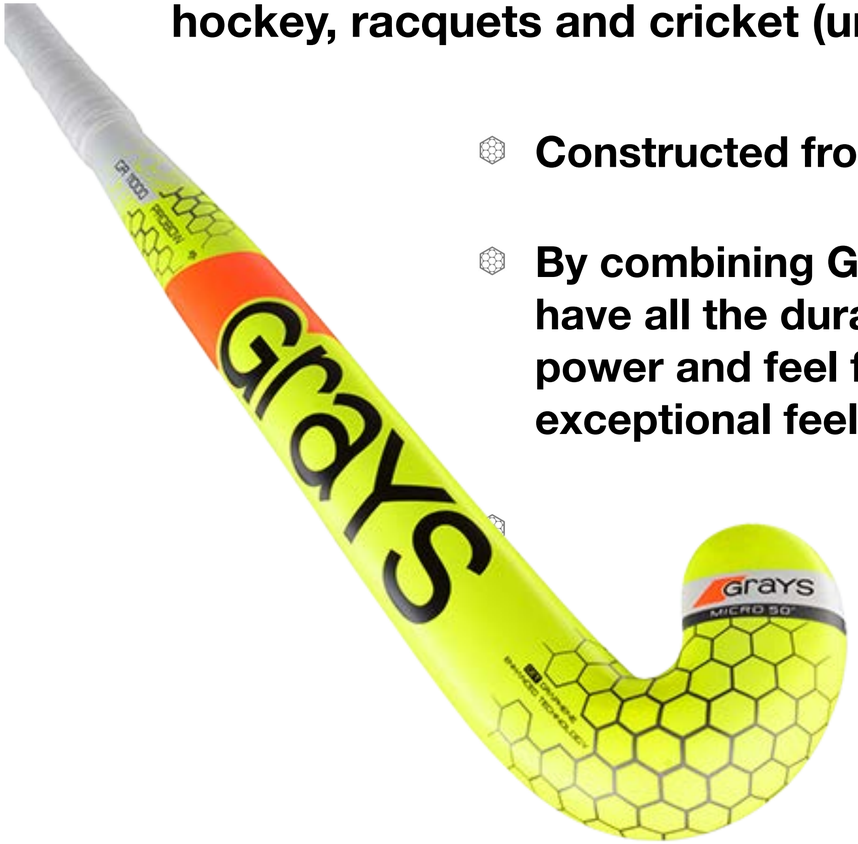
The 4.5-meter high (approx. 14 feet), lightweight arch is being tested on outdoor track at Network Rail's workforce development center in Bristol, UK.

Aecom has partnered with UK engineering firm Scaled to develop the detailed design and prototypes of the CNCTArch using large-scale 3D-printing techniques. Scaled uses its 3D printer, one of the largest in Europe, to print the product in the new graphene-reinforced polymer, which is supplied by Aecom's materials partner Versarien plc.

Graphene Application Examples

Grays

Grays was founded in Cambridge by world rackets champion H.J. Gray in 1855 and supply quality sports equipment; notably for hockey, racquets and cricket (under the Gray-Nicolls brand).



- **Constructed from carbon, aramid, and graphene.**
- **By combining Graphene into the composite matrix; “players will have all the durability and playability of GX technology, with extra power and feel from Graphene. Sticks in the GR range offer exceptional feel, power and playability.”**

Graphene Application Examples

Italian Institute of Technology (IIT) and Momodesign

Motorcycle helmet - graphene is incorporated into the exterior shell as a coating. The graphene dissipates heat quickly across the helmet.

- **Uses few- and multi-layer graphene flakes in a powder that is mixed into a solution and then spray-coated on the exterior shell of the helmets.**

Graphene Application Examples

Haydale graphene-enhanced prepreg has now been incorporated in the composite tooling and automotive body panels of the new 'BAC Mono R'.

Utilisation of graphene-enhanced tooling materials offers the potential for significant improvements in the following aspects:

- **The coefficient of thermal expansion (CTE) – is more closely matched when using composite tooling. A key issue with the use of metal tooling is a significant mismatch in (CTE)**
- **The need for superior quality – higher dimensional stability tooling is increasing the demand for composite tooling**
- **Current composite tools also suffer from a finite life - wearing of the tool surfaces and microcracking. The use of graphene has the potential to increase the life of the tools.**

50% improvement in tensile strength and stiffness

Graphene Application Examples

Carbon fibre-reinforced composite (CFRP)

Test results, untreated versus graphene enhanced material.

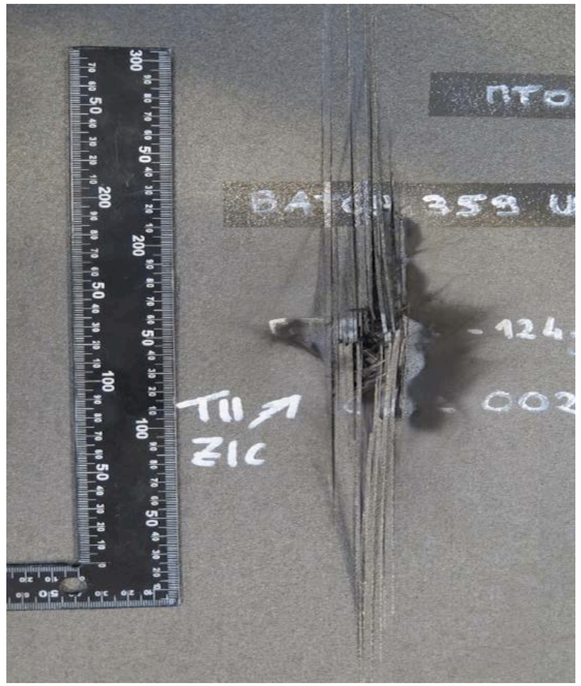


Figure 1: Back face of unmodified panel after lightning strike showing punch-through

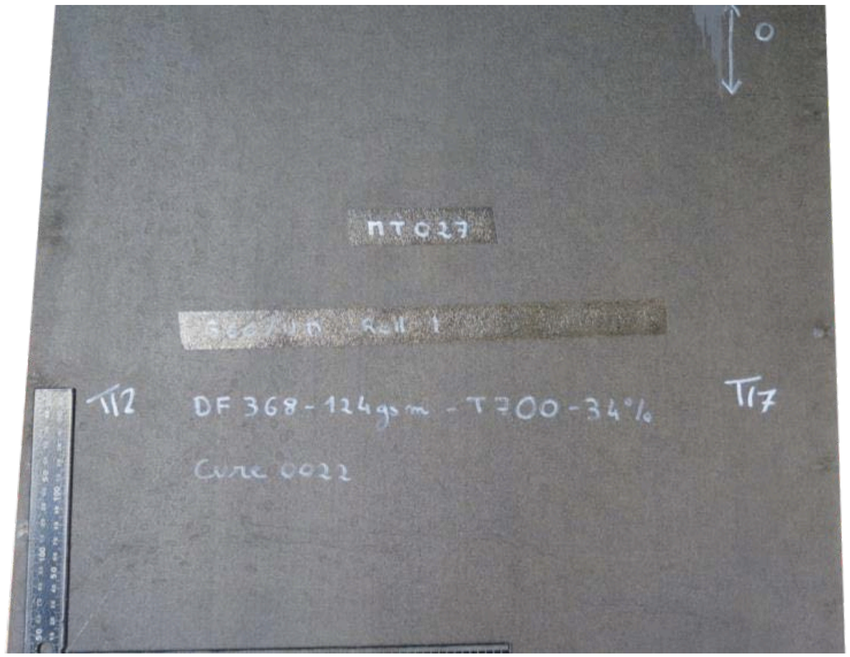


Figure 2: Back face of Haydale-modified panels after lightning strike showing no visible damage

Graphene Application Examples

Carbon fibre-reinforced composite (CFRP)

- 600% increase in through-thickness electrical conductivity of laminates with scope to increase by several orders of magnitude.
- Strength properties equivalent or better than control material.
- Demonstrator produced proving manufacturing and demonstrating a typical Lightning strike zone 2/3 application.
- Potential for the reduction/elimination of parasitic mass (copper mesh) leading to lower manufacturing costs and mass saved.
- Other areas of application:
  - EMC and RF Shielding application such as electronic enclosures
  - Anti-static, aircraft ducting and piping, interior
  - Most applications using CFRP/GRP that need metal coatings for reflectivity/conductivity

Graphene Application Examples

GRAPHENE PRODUCT CASE STUDY

dassi

GRAPHENE ENHANCED CFRP FOR A LIGHTER, FASTER RACING BIKE

50% ⬆ FRACTURE TOUGHNESS

30% ⬇ LIGHTER

70% ⬆ INTER-LAMINAR SHEAR STRENGTH

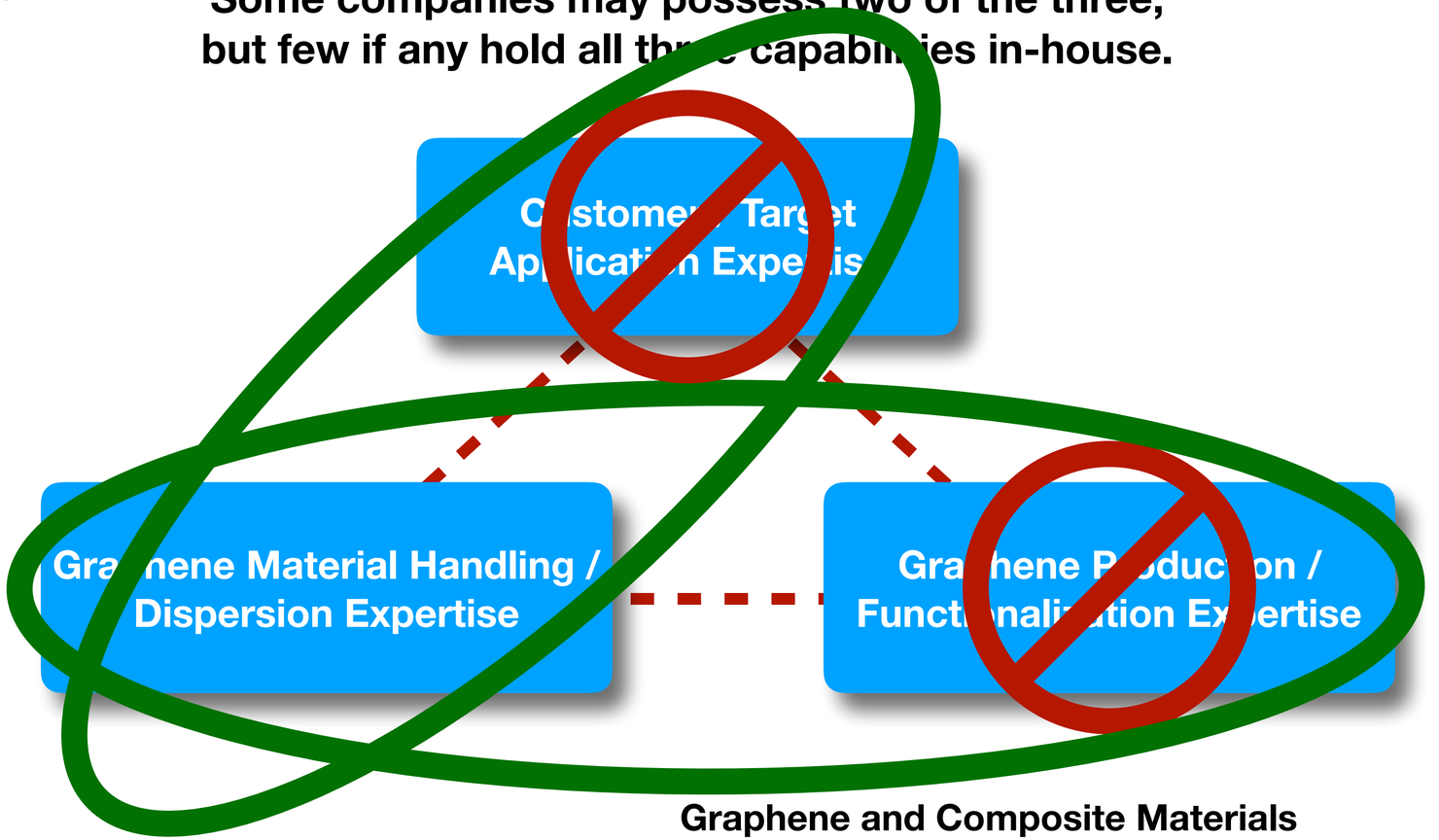
The Dassi Interceptor Graphene weighs just 750g, but records the same stiffness and strength characteristics of a 950g carbon fibre frame

Graphene Sourcing and Application Development

- The morphology and functionalisation of the graphene material is critical to how it performs in a given application. Often the graphene must be “tuned” to the customer’s requirements.
- A graphene supplier must be able to provide consistent material at scale.
- Material handling and dispersion capabilities are critical to material performance.

All three competencies are required for a successful graphene enhanced application.

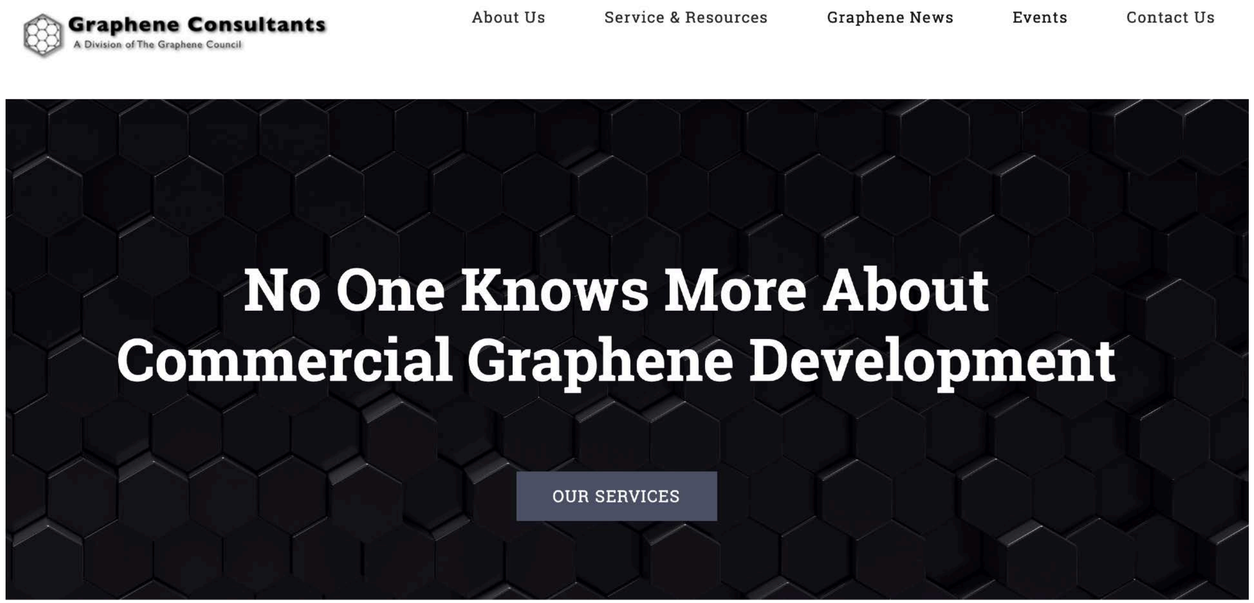
Some companies may possess two of the three, but few if any hold all three capabilities in-house.



How The Graphene Council Can Help

The Graphene Council

- Company Membership gives you access to industry intelligence, market reports and supplier / application development matchmaking support.
- Custom advisory services available with graphene experts from academia and industry, world-wide.
- Verified Graphene Producer™ and Verified Graphene Product™ programs.



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Questions?