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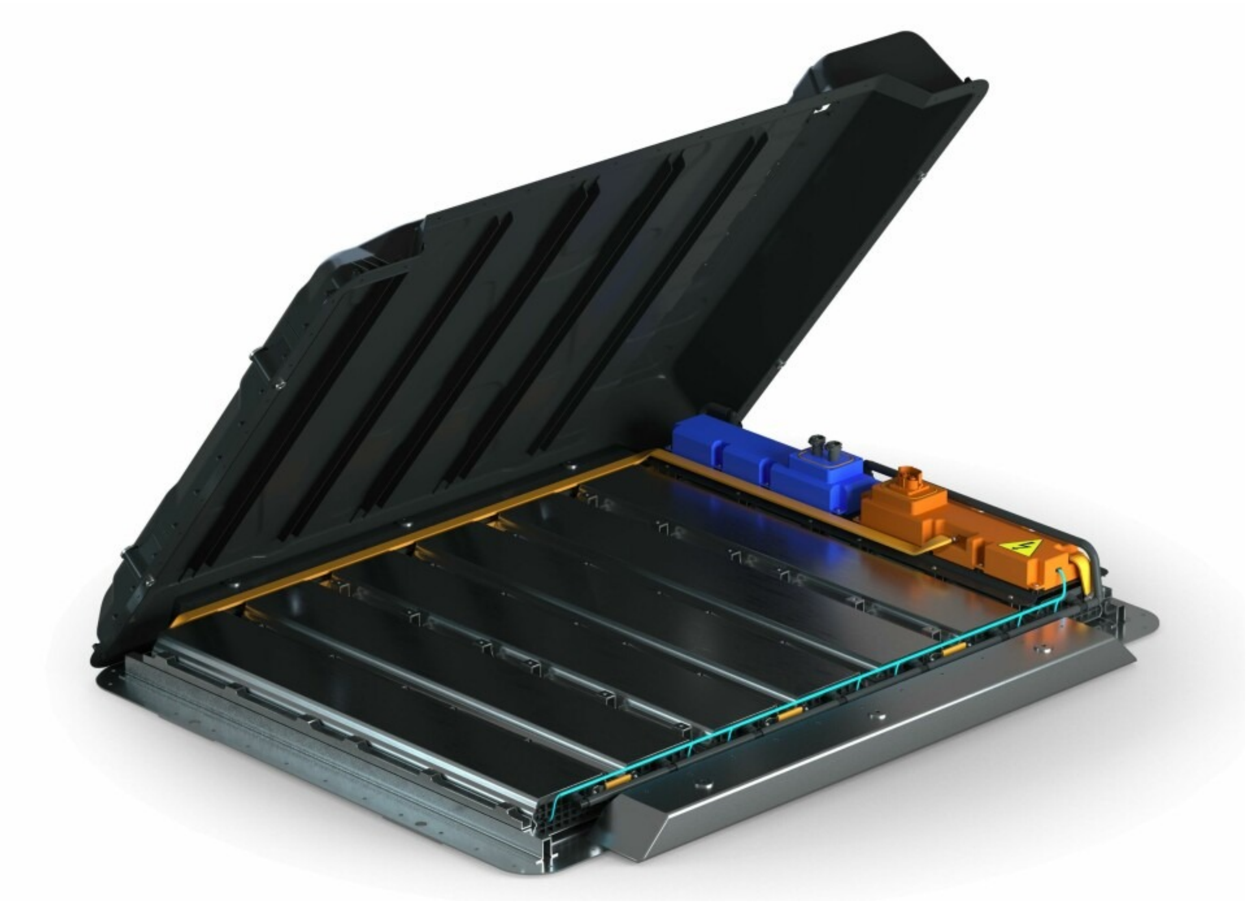

Development of Lightweight, Sustainable and Multifunctional Battery Pack Materials in Electric Vehicles

Master's thesis in Industrial and Materials Science

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Material enhancement for EV battery pack and pouch cell laminate
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Cover: The high-voltage battery pack of an electric vehicle, with its cover opened to show the internal components.

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Abstract

Accelerated needs for battery electric vehicles (BEVs) drive materials requirements toward lightweight, mechanically stable, and environmentally friendly battery packaging materials beyond metal-rich systems. This thesis explores the GO/rGO polymer coatings as multifunctional layers for two packaging sectors, namely, CF skins for battery enclosure and PA/PE films for pouch laminates. A focused literature benchmark is supplemented with experiments performed on coated CF and PA/PE coupons at 1, 3, and 5 wt% graphene loadings. Performance was characterized via peel load–displacement (interfacial adhesion and failure mode), tensile testing (mechanical integrity of coated substrates) and a 48 h deionized-water soak (moisture stability).

Results demonstrate that low-to-moderate loadings (1-3 wt%) provide robust adhesion and mechanical performance on both CF and PA/PE, whilst coatings remain stable after soaking. On the other hand, 5 wt% early debonded, synergetic particulate detachment and worse mechanical behavior, indicating interfacial instability. Such results bring valuable design guidelines to metal-lean/metal-free battery packaging: constraining graphene in a 1–3 wt% window and adopting graded coatings (less loading on adhesion-critical interfaces, moderate loading on reinforcing or tortuosity-barrier sites). This route enables lightweight CF enclosures and metal-free pouch laminates, which are in line with the sustainability targets. The leading next-step priorities are quantitative WVTR/OTR, electrolyte ageing and thermal/abuse propagation studies, as well as life-cycle analysis (LCA) and scalability considerations.

Keywords: graphene oxide (GO); reduced graphene oxide (rGO); carbon fiber (CF); polyamide (PA); polyethylene (PE);water vapour transmission rate (WVTR); oxygen transmission rate (OTR); battery electric vehicle (BEV); tensile testing; peel adhesion; pouch cell laminate;

Preface

This thesis is a product of the Master's programme in Industrial and Materials Science at Chalmers University of Technology and was completed in the spring of 2025. The topic of this research was the development of lightweight, sustainable and multifunctional materials for electric vehicle battery pack applications.

The project has been nothing short of an inspiring and tough adventure that intermingled material science, sustainability, and engineering design. It has been possible for me to sharpen my technical and analytical skills as well as to develop a comprehensive understanding of the role that the so-called advanced materials play in the move towards cleaner mobility.

I want to express my deep gratitude to each and every one at the Department of Mechanics and Maritime Sciences for their help, support and for making a stimulating research atmosphere which was conducive to this work.

Acknowledgements

I want to express my sincere appreciation to Komal, PhD researcher, for her unremitting guidance, encouragement, and support during the whole process of this thesis. Her qualifications, temperament, and positive criticism were very helpful in the development of my work and in my struggle with numerous obstacles at the same time.

I would also like to extend my gratitude to my examiner, Dr. Jinhua Sun, from the Department of Mechanics and Maritime Sciences, for his penetrating remarks, considerate recommendations, and useful tips that hugely helped in the elevation of this research's quality.

My gratitude goes further to my fellow students as well as fellow researchers for their partnership, sharing of ideas, and good spirit around the project. I appreciate the technical support in the lab for their expertise and for making it so that the experimental work went on without interruptions.

Finally, my heartfelt thanks go to my family and friends who have been my rock, my support system, and my well wishers all the way through my studies. Their faith in my abilities has been a very strong and energizing factor throughout my journey.

Gothenburg, October 2025.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

Al	Aluminium
BES	Battery Energy Storage
BMS	Battery Management System
BOPA	Biaxially Oriented Polyamide
CFRP	Carbon Fibre Reinforced Polymer
CFRTP	Carbon Fibre Reinforced Thermoplastic
CPP	Cast Polypropylene
CSMO	Carbon-Supported Magnesium Oxide
CtC (CTC)	Cell-to-Chassis
CtP (CTP)	Cell-to-Pack
DER	Distributed Energy Resource
ESS	Energy Storage System
EV	Electric Vehicle
FST	Fire, Smoke, and Toxicity
GO	Graphene Oxide
HDPE	High-Density Polyethylene
HEV	Hybrid Electric Vehicle
LIB	Lithium-Ion Battery
MG	Microgrid
MILP	Mixed-Integer Linear Programming
MMC	Metal Matrix Composite
MTP	Module-to-Pack
NVH	Noise, Vibration, and Harshness
OTR	Oxygen Transmission Rate
PA	Polyamide
PCM	Phase Change Material
PE	Polyethylene
PET	Polyethylene Terephthalate
PET/PP	Polyethylene Terephthalate / Polypropylene
PV	Photovoltaic
RES	Renewable-based Energy Sources
rGO	Reduced Graphene Oxide
SoC	State of Charge
TMS	Thermal Management System
UTS	Ultimate Tensile Strength
WVTR	Water Vapour Transmission Rate
YS	Yield Strength

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Parameters

ρ	Density of the material (g/cm^3).
k	Thermal conductivity (W/m $\cdot$ K).
E	Young's modulus or elastic modulus (GPa).
UTS	Ultimate tensile strength (MPa).
YS	Yield strength (MPa).
T	Temperature (°C) used for drying or curing.
F	Force or load applied during tensile or peel testing (N).
v	Crosshead speed in the UTM test (mm/min).

Variables

σ	Stress (MPa) obtained during tensile testing.
ϵ	Strain (%) corresponding to specimen deformation.
P	Peel load measured in adhesion test (N or N/25 mm).
Δd	Displacement during mechanical testing (mm).
θ	Peel angle in adhesion test (°).

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Introduction

1.1 Background: The Global Imperative for Electric Vehicle Battery Innovation

The worldwide move to clean energy abroad, underpinned by strict climate policies and rising consumer acceptance, makes the Electric Vehicle (EV) one of the central components of future infrastructure for transportation. Such a quick transition drives the complete optimization of each system integrated into EV, especially concerning the LIB pack as a core energy source in the vehicle. The scope of this change is staggering: while global EV sales totalled 17.8 million units in 2024, it will more than double by 2030 to hit 40.1 million, creating battery demand that is projected to exceed 1 TWh in just five years. This exponential growth necessitates the development of new technologies that address current limitations in energy storage, system-level device efficiency, cost-competitiveness, and sustainability throughout its lifecycle. Figure 1.1 shows the annual global EV sales in the world. China, the United States, and Germany are the leading countries in the purchase of electric vehicles. Based on several analyses, the world's EV market may exceed 60 million vehicles sold in one year by 2040.[1]

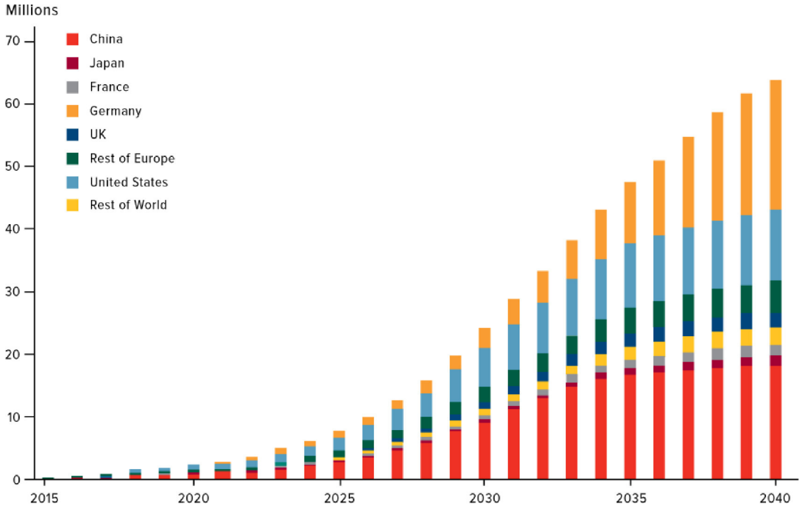

Figure 1.1: Annual demand forecast for EVs in the world

With the rise to prominence of energy storage systems (ESSs), particularly batteries, in recent years, both the direct and indirect benefits to human life have improved.

The significance of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) to humanity is substantial, as they contribute to reducing the emission of harmful gases in the environment, which has an adverse long-term effect on human lives. The other significant advantage of batteries in EVs is that they alleviate a certain degree of force associated with fossil fuels, including petrol and diesel. They reduce the need for fossil fuels, save them for other purposes and lower the rate at which they are extracted from the natural reserve. As batteries are the core parts in EVs and HEVs, their performance substantially influences the market prospects of EVs and HEVs. Hence, car manufacturers are looking for betterment in their vehicle battery technology and BMS, as well as cheap and reliable batteries that they should invest in.[1]

The effect of the battery pack on vehicle performance is fundamentally related to its weight. Since the pack accounts for 25% to 35% of the vehicle mass, it is not difficult to understand why weight optimization of any non-active parts (i.e., structural enclosure and packaging material) is critical. By lightening the package, you are directly improving the overall available gravimetric energy (Wh/kg) on board the vehicle, potentially leading to more range or enabling smaller, cheaper battery packs that deliver equal range.

Importantly, in light of an ever-increasing research resource on improving cell-level energy density by optimizing the chemistry (e.g. new cathode materials or advanced anodes), the collective economic and environmental impact of non-active battery pack material is realized to be a critical frontier for research activities today. Continuing a historic decline in the price of battery packs, which recently dropped to 115 per kilowatt-hour (kWh), with anticipated decreases ongoing into 2025. Materials innovations, including carbon-fiber-reinforced polymers (CFRP), have become a promising candidate as substitutes for traditional metals. Similar to aluminium, the carbon fiber reinforced plastics (CFRP) can possess a high strength-to-weight ratio with a density between 1.5-2.0 g/cm^3, in contrast to the aluminium density of ≈2.7 g/cm^3 and will enable enclosure weight savings in the range of 40 to 60%. In addition, developments in graphene polymer composites are improving film barriers and mechanical stability for pouch cell laminates. Innovations in material choice and manufacturing processes for both the enclosure and its internal parts are necessary.

Aside from performance and cost, the amount of material required for TWh production scale has intensified interest in the circular economy. The critical raw materials needed, such as lithium, cobalt or nickel, are also facing possible shortages and ethical supply challenges. Therefore, the choice of packaging materials in terms of their light weight and recyclability or reusability is a necessary strategy for value-providing resilience to the LIB supply chain. The transition is thus moving away from a sole focus on improving chemical energy density to one of systems efficiency, where new multifunctional structural materials are needed to optimize both mass and environmental impact.

1.2 The Strategic Necessity for Advanced Battery Pack Research

The electric vehicle battery pack has evolved from an attached module to a key strategic material in modern transportation systems, determining the cost and endurance mileage of EVs based on its maturity. This industrial readjustment requires a multidisciplinary and sustainable scientific approach to battery pack architecture and materials, grounded on overpowering economic, performance and environmental issues.[7]

1.2.1 The Economic Imperative: Cost Compression and Parity

The sound basis for further development of the battery pack is provided by the goal to maintain an aggressive market growth and reach a cost of ownership parity to ICE vehicles.

Reinforcing Exponential Market Growth: Global EV sales are expected to surpass 21.3 million units by 2025, with combined battery pack energy capacity demand also projected to exceed 1 Terawatt-hour (TWh) in the same year. This industrial-scale behemoth drives the need for supply chain stability and high-volume, low-cost manufacturing like we have never seen. Hence, future research should be directed towards structural innovations, including the module-less CtP (Cell-to-Pack) designs that offer an instantly higher system-level energy density and minimal manufacturing complexity.[8]

Table 1.1: Strategic Drivers for EV Battery Research

Research Driver	**Metric/Constraint**	**Benchmark/Target (Academic & Industry)**
Economic Imperative	Battery Pack Cost	Decline from ≈ \$122/kWh (2023) to ≈ \$80/kWh (2026 forecast) to achieve cost parity with ICEs
Performance & Range	Energy Density Target	Top-tier density target of 600 to 800 Wh/kg by 2030
Safety & Longevity	Mechanical Integrity	Must manage anode volume expansion (up to 300% for Si)
Sustainability	Supply Chain Resilience	R&D is needed to reduce reliance on volatile metals (e.g., Cobalt, Lithium)

Closing the Cost Gap: Li-ion battery costs have fallen by about 90% since 2010, from \$1,400 per kilowatt-hour (kWh) to nearly \$100/kWh. However, ensuring mass adoption will depend on achieving more aggressive cost targets. Average battery pack prices are projected to drop to just below \$80/kWh by 2026 for unsubsidized cost parity with gasoline cars, according to Goldman Sachs Research. As we adopt a low-cost environment, achieving and maintaining this cost advantage will require ongoing technical innovations in pack design and material substitution (beyond just the deflationary effect of commodity prices) to drive efficiency and reduce component costs.[8]

1.2.2 Performance and Safety Barriers

The electric vehicle battery pack currently used faces limitations that only R&D can resolve.

- **Mechanical stress:** Third-generation high-energy density chemistries that employ silicon as the anode present a serious mechanical risk due to volume expansion reaching even 300%, with packaging needed to mitigate electrode pulverization and fracture. This requires materials of high stability and robustness.[2]
- **Safety and Thermal Management:** The Battery system is the heart of an EV; its advanced maturity determines the cost and mileage fulfilment. The sophisticated operation of the Battery Management System (BMS) and Thermal Management System (TMS) is critical for obtaining safety, long life span and cost. Materials and Parts Development R&D shall provide a crashworthy, thermally well-isolated material.[3, 4]

1.2.3 Sustainability and Resource Resilience

With the massive scale of electrification anticipated – global battery demand will reach more than 1 TWh in 2025 – this puts new strains on an already tight supply chain.

- **Raw Material Criticality:** The looming gap between available mining capacity and growing demand for vital metals (lithium, nickel, cobalt) has stirred concern among analysts about price swings and ethical sourcing issues. It is essential to allow time for researching sustainable materials that are either less resource-intensive to produce or suitable for a circular economy, so we can achieve long-term security of supply.
- **End-Of-Life Packaging:** Shifting to advanced materials such as CFRP allows for up to 40% weight reduction, but the environmental advantage slides with better end-of-life strategies, including ease of disassembly and a high recycling rate process.

1.3 Purpose

This thesis aims to explore and assess the possibilities of lightweight, multifunctional, sustainable composites for the future EV battery pack. The research is centered on the fabrication and characterization of graphene–polymer composite coatings deposited onto carbon fiber (CF) as well as polyamide (PA) / polyethylene (PE) films. These coatings are found to exhibit high mechanical robustness and adhesion strength, as well as overall chemical resistance, which makes these systems promising candidates for metal-free level packaging rather than traditional aluminium-based packaging.

Both literature review and experimental validation are aspired to support crossing the gap between material design conception and functional performance of graphene–polymer coated composites, contributing on advanced lightweight battery pack architectures targeting sustainability and performance goals in electric mobility.

1.3.1 Aim

To investigate and evaluate lightweight, multifunctional, and sustainable composite materials for next-generation electric vehicle battery packaging, focusing on mechanical robustness, adhesion, and environmental performance compared to conventional metallic systems.

1.3.2 Goals/Objectives

The specific goals of this research are:

- To review recent advancements in lightweight and multifunctional materials used in EV battery enclosures, particularly CFRP and hybrid composites.
- To develop and characterize graphene-polymer composite coatings on carbon fibre, PA, and PE films for improved mechanical strength, adhesion, and stability.
- To assess the potential of metal-free (graphene-polymer) laminates as sustainable alternatives to aluminium-based pouch cell packaging.
- To evaluate the performance of coated films through mechanical, adhesion, and stability testing.
- To identify structure-property relationships and propose optimized coating compositions for multifunctional, lightweight battery packaging solutions.

1.4 Research Questions

The investigation is structured around three primary research questions, designed to systematically test the viability and performance of the proposed material innovations against established automotive requirements:

1. What are the recent advancements in lightweight and multifunctional materials for battery packaging, and how do carbon-fibre-reinforced polymer (CFRP) systems compare with conventional metallic enclosures in terms of mechanical robustness and sustainability?
2. How does the integration of graphene-polymer composites as coatings on carbon fibre, PA, and PE films enhance the mechanical strength, adhesion, and stability of battery packaging materials, compared to conventional aluminium-based laminates?
3. Can metal-free packaging laminates (graphene-polymer composite coatings on PA/PE films) achieve adequate barrier and mechanical performance for pouch

cell applications, while maintaining lightweight and environmentally sustainable characteristics?

1.4.1 Research Contribution

The main accomplishments of this research include:

- **Quantitative mechanical benchmarking (RQ1):** This study provides material performance data through a comprehensive literature review and comparative mechanical testing of CFRP and metal systems, which is necessary to confirm composites as a superior structural solution to metal for automotive battery enclosures.
- **Systematic Verification of Nanocomposites Interfacial Properties (RQ2**): The study presents a systematic experimental investigation on how GO/rGO incorporation at 1, 3 and 5 wt% improves the interfacial adhesion (peel load) and mechanical properties (tensile strength) in CF structural skins and PA/PE films. This is important to develop materials that meet the dynamic mechanical requirements of more advanced cells.
- **Feasibility Study of Laminate stability in Metal-Free Battery (RQ3):** The proposed work for RQ3 will deliver a direct impact to the sustainable target of metal-free pouch cell, as demonstrated by investigating the mechanical integrity and moisture stability of laminates when idealized graphene-polymer coating is utilized. The performance of these films is quantified using peel, tensile and 48 h soak tests to consider them as potential sustainable alternatives to the conventional aluminium-based packing materials.

1.5 Limitations / Demarcations

In this study, the following limitations are identified to confine our analysis and provide high-quality answers:

- **LCA Exclusion:** This article incorporates a literature review and argumentation about the environmental benefits of CFRP compared to aluminium (to answer RQ1), but it does not assiduously perform or collect primary data for an LCA.
- **Barrier Test Exclusion:** Discussion of barrier properties for the metal-free laminate (in RQ3) will be confined to mechanical and moisture ingression resistance (48 h immersion in deionized water). The intrinsic barrier properties (i.e., water vapour transmission rate (WVTR) and oxygen transmission rate (OTR)) are not experimentally measured in this work.
- **Material Focus:** This is purely focused on the development, manufacture and testing (processing and mechanical automated tests) of passive materials (enclosure CFRP and PA / PE laminates). It does not contain original research or electrochemical testing of the active cell chemistry (anode, cathode or electrolyte).
- **Scaling:** Structural testing, which relates to RQ1, is completed on representation test coupons and standard sub-assemblies to prove material properties, not an automotive-level crash test of a battery pack.

1.6 Report Structure

This thesis report is systematically organized into five chapters, which address the stated research questions and objectives.

- **Chapter 1 (Introduction):** Provides background information, justification, work description and objectives of the project.
- **Chapter 2 (Theory/Literature Survey):** Presents an extensive background on fundamentals: state-of-the-art battery pack structures, advanced structure CFRP composites, mechanics of graphene-polymer nanocomposites and existing standards on mechanical performance and moisture stability reliability in the packaging for batteries.
- **Chapter 3: (Methods)**: Details the experimental and analytical methodologies employed, including the fabrication techniques for graphene-polymer coatings (at 1,3, and 5 wt% loadings), and the protocol for mechanical testing (peel, tensile, and 48 h soak tests).
- **Chapter 4 (Results)**: Provides experimental data and discussion, for the mechanical performance of composite type (RQ1), the improvement in interfacial adhesion and tensile strength achieved by GO/rGO coatings (RQ2) and stability of metal-free laminates after 48 h water soaking (RQ3).
- **Chapter 5 (Conclusion):** Summarizes the results, makes concluding remarks on the viability and durability of the proposed material systems, highlights the significant contributions to knowledge and recommends future work.

2

Theory

This section discusses a comprehensive literature review on EV battery pack design and development. It covers the basic structure and design of battery packs, their main functions, and how they are mounted inside a vehicle. The chapter also discusses the development of enclosure materials and a new genre of composites, including carbon–fibre–reinforced composites and graphene–polymer systems. It also focuses on pouch cell designs, addressing some of the current challenges in achieving lightweight, sustainable, high-performance battery pack materials.

2.1 Structure of Electric Vehicle Battery Pack

In an electric vehicle (EV), a battery pack is the primary energy storage device, as it converts stored chemical energy into electrical power for propulsion of the vehicle. It is a highly complex system with strict constraints, for example, energy density, safety, thermal performance and structural durability, which often accounts for 30-50 % of the vehicle weight and costs. By 2025, lithium-ion (Li-ion) batteries are expected to be predominant, with a continued focus on solid-state battery development for higher density and safety. These batteries are characterised by cells, which are then assembled into modules. Ultimately, the assembly of an entire enclosure, the hierarchy of the pack has been developed with scalability in mind, as well as ease of maintenance and integration into the underbody of a vehicle as part of its skateboard architecture. This layout takes advantage of underfloor volume usage to decrease the centre of gravity, improve handling, and creates a sandwich with the floor that increases bending and torsional stiffness (targets: 11 kN/mm bending, 1500 kNm/rad torsional)[5, 6]. 4.8 describes the main components of battery pack and their roles.

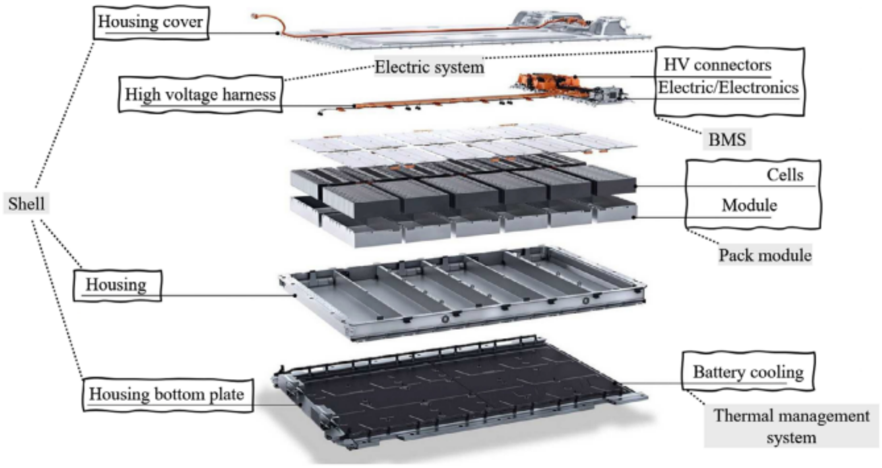

Figure 2.1: EV battery pack structure

- **Housing Cover**
  A top-mounted enclosure shields sensitive components from mechanical impact, dust and moisture ingress. It also acts as an electromagnetic shield and a mounting point for sensors and electrical contacts.
- **High Voltage Harness**
  Insulated high-voltage wire is used to connect the modules, BMS, and inverter together. It safely manages the power between cells and the vehicle powertrain.
- **HV Connectors / Electrical System**
  These connectors provide secure power transmission and high-voltage isolation (typically 400–800 V). They feature interlocks, fuses and contactors for safety.
- **Battery Management System (BMS)**
  The BMS is responsible for cell and module voltages, currents, and temperature monitoring. It could control the cell balance, state of charge(SoC) and thermal safety to avoid overcharging and discharging.
- **Cells and Modules**
  Cells: Basic electrochemical energy storage units.
  Modules: Groups of cells connected in series and parallel either mechanically or electrically into manageable packages.
  These establish the combined capacity, voltage, and power output of a pack.
- **Pack Housing / Frame**
  The building block that encases and protects all other modules. It provides stiffness, crash protection and vibration resistance and is frequently formed from aluminium or composites.
- **Housing Bottom Plate**
  Provides chassis rigidity and crash resistance from underneath the chassis. It may also include inlaid fire-retardant or insulating layers.
- **Cooling / TMS (Thermal Management System) of the Battery**
  It is positioned under or between your modules and manages cell temperature with liquid cooling plates or refrigerant channels. Good thermals not only help you produce the best performance but also keeps your battery running.

2.1.1 Key Functions of Battery Pack Enclosure

The main functions and critical aspects of the battery pack are listed in the following section, according to [6]

- **Structural stability**: the battery pack needs to be structured to support the cells well enough so that they are not deformed and performance is not affected. It must be structurally integrated into the vehicle underbody in a way that reliably supports static and dynamic loads, while preventing the transmission of noise, vibration, and harshness (NVH).
- **Placemen**t: with the battery pack resting as low in the chassis as possible, your vehicle gains stability thanks to a lowered center of gravity. In addition, the location of the pack is also essential for vehicle packaging and passenger ergonomics, so it is an important aspect of overall vehicle design.
- **Underbody stiffness**: In modern hybrid and electric vehicle design, the battery pack frequently is a structural member. When combined with the undercarriage, it is among others a promoter of rigidity/stiffness of the entire vehicle and forms, in a sandwich construction-like manner, an increased longevity and crash resistance.
- **Crash protection**: during a crash, the battery pack has to be protected by efficient crash-absorbing structures to avoid deformation or penetration. It is known that short-circuits, or other causes of thermal runaway, can occur from very mild mechanical damage to the pack; thus, it may be vitally important that a high level of structural integrity is maintained in an impact for safety reasons.
- **Thermal management**: battery cells have their best operating conditions within an ideal temperature range of about 25–35 °C, and the thermal management system keeps them in check by warming or cooling as necessary to avoid overheating or coldness. The battery life is improved as long as the values are inside this range, which means that it will have nearly constant performance under many operational conditions.
- **Protection from external environment**: The package has to be protected against the environment, including submersion, projectile impact and penetration. Sufficient clearance between the ground, the tough outer casing and a well-sealed interior, which protects internal mechanisms from being destroyed and enhances year-round conduct, especially during rough riding conditions.

2.2 Role of Packaging in EV Performance and Safety

A transformation is taking place in the worldwide automotive industry, and at its very core, this transformation is driven by the battery electric vehicle (BEV) - a shift toward sustainable transport. At the core of every electric car is its battery pack, which dictates everything from its abilities and driving range to how fast it can charge and even how long it is likely to last. This source is not only an energy store; it also represents the most expensive, technologically challenging and fail-tolerant system of an electric vehicle's powertrain [9]. The basic engineering difficulty of the battery pack is adding up hundreds or thousands of individual packs of cells, each generating only 3-4 volts, to create an integrated high voltage DC power supply that can supply 400-800VDC or more to the automobile's traction motor [10]. This packaging process is much more than just an assembly step; it is multi-disciplinary engineering that involves tradeoffs of mechanical strength, thermal stability, electronic control and manufacturable features.

Traditionally, hierarchical and modular architecture has been the predominant design philosophy, exemplified by the Cell-to-Module-to-Pack (MTP) approach. This traditional approach requires a self-explanatory, step-by-step build. One or more cells are first assembled into enclosed operable sub-units referred to as modules. The modules are then combined and linked together within a secondary ruggedized enclosure to create the finished battery pack. This approach separates the concrete chemical processes, which are health-, safety-, and environmentally focused during cell manufacturing, from the basically mechanical and electrical assembly procedure of modules and packs. Two main benefits of this incremental design are its serviceability – replacing a module instead of an entire pack – and its scalability; a manufacturer can take the same module design to multiple vehicle set-ups.

Except that the never-ending pursuit of more extended driving range, lower vehicle costs, and better performance has revealed that there are inherent limitations in the modular strategy [10]. Non-structural, wiring and hardware for each module contribute size and mass to the pack that do not act as energy storage elements, thus limiting pack-level specific energy. As an answer to these inefficiencies, the industry is shifting quickly towards disruptive architectural paradigms, which are centred on integrability. These next-level paradigms, categorized as cell-to-pack (CTP) and cell-to-chassis (CTC), challenge the basic tenets of what a battery is. In CTP modularity, the middle module step is bypassed entirely, and cells are built directly into the pack structure. The CTC takes it a step further, eliminating the need for a dedicated pack housing by integrating the battery cells directly into the vehicle's chassis, thereby transforming that small electronic component from a passive to an active load-bearing structural element [11, 12]. A comprehensive review of these battery pack architectures is presented in further sections of this chapter.

2.3 Evolution of Battery Pack Architectures

The traditional Module-to-Pack (MTP) architecture, which has been validated and is very reliable, also comes with "packaging overhead." The module housings and fasteners, along with pages of wiring, also contribute to the overall energy density in the battery pack by weight and volume. To address these challenges and further reduce the price of electric vehicles, the industry has developed more sophisticated packaging architectures that progressively eliminate non-critical elements by integrating them at higher levels. This transformation is most suitably described as a movement from MTP (module to pack) toward CTP (cell to pack), with the destination being CTC (cell to chassis) [14, 15]. Figure 2.2 visually represents battery

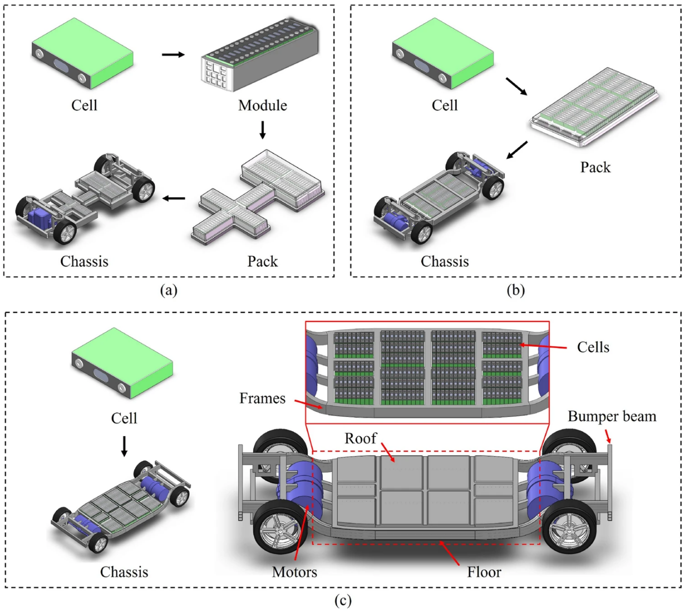

Figure 2.2: a) typical scheme, MTP, b) CTP scheme and c) CTC scheme

pack architecture integration concepts [16]. Furthermore, the comparison presented in Table 2.1 is included to illustrate the key differences between various battery pack integration strategies used in modern electric vehicles.

Table 2.1: Comparison of Battery Pack Integration Architectures

Feature	**Module-to-Pack (Conventional)**	**Cell-to-Pack (CTP)**	**Cell-to-Chassis (CTC) / Structural Battery**
Key Principle	Cells are grouped into modules; modules are assembled into a pack.	Cells are integrated directly into the pack, eliminating modules.	Cells are integrated directly into the vehicle's body/chassis structure.
Gravimetric Efficiency	Low (typically 40–60% cell-to-pack mass ratio)	High (typically >75%)	Highest (can achieve "negative mass" by replacing structural parts)
Volumetric Efficiency	Low (significant volume used by module hardware)	High (volume utilization can exceed 70%)	Highest (utilizes vehicle structural volume for energy storage)
Part Count / Complexity	High (many module components, fasteners, wires)	Medium (module components eliminated, simplified assembly)	Lowest (pack enclosure and many chassis parts eliminated)

Continued on next page

Table 2.1 (continued)

Feature	Module-to-Pack (Conventional)	Cell-to-Pack (CTP)	Cell-to-Chassis (CTC) / Structural Battery
Manufacturing Process	Multi-stage: cell-to-module, module-to-pack, pack-to-vehicle.	Simplified: cell-to-pack, pack-to-vehicle. Pack can be produced offline.	Highly integrated: cells are installed directly into the chassis on the main vehicle assembly line.
Serviceability / Repair	Highest (individual modules can be replaced)	Low (cell replacement is difficult to impossible; often requires pack replacement)	Very Low / None (cell failure or crash damage may require chassis replacement)
Key Proponents / Examples	Most early-generation EVs (e.g., Nissan Leaf, Chevrolet Bolt)	BYD (Blade Battery), CATL (Qilin Battery)	Tesla (4680 Structural Pack), Leapmotor

2.4 Materials for Electric Vehicle Battery Pack Enclosures: From Traditional Metals to Advanced Composites

Electric vehicle battery pack enclosure materials have transitioned from conventional metals such as steel and aluminium to new-age composites, including carbon fibre-reinforced polymers (CFRP) and metal matrix composites (MMCs), such as aluminium/silicon carbide. Composites can allow enclosure butcher blocks to weigh 56% less and receive built-in cooling, especially with phase change materials. However, such materials need to be meticulously designed to overcome possible mechanical strength losses as a result of thermal loads. Hybridization between metals and composites is bringing about new ways to maximise fire protection and crashworthiness while minimising weight. Developments in rapid-cure and electro-thermal in-situ cure methods additionally improve the manufacturability and properties of these materials.

Traditionally, enclosures were fabricated out of steel or aluminium for their strength and ease of manufacturing. But the demand for lighter, safer and eco-friendlier automotive cars has compelled a shift towards advanced composites and hybrid material technology [17]. This report section reviews the development, relative performance, processing challenges, environmental consequences and future trends of the materials employed in EV battery pack enclosures with particular emphasis on the transition from metallics to advanced composites and multi-functional materials.

2.5 Comparative Analysis of Material Properties

This section presents an analysis of key material properties, including weight, mechanical strength, thermal management performance, cost considerations, fire resistance, and impact resistance of the battery pack enclosure.

2.5.1 Weight and Mechanical Strength

- **Traditional Metals:** steel provides excellent strength and crash protection, though it's heavy and drains the range of an electric vehicle. Aluminium alloys also offer a 30–40% weight reduction relative to steel with acceptable strength and manufacturability [17, 18].
- **Metal Matrix Composites (MMCs)**: high specific stiffness and strength together with good thermal conductivity can also be achieved by aluminium/silicon carbide (Al/SiC) MMCs, but at much lower mass. Crash absorption and fire resistance are also improved with open-pore MMCs [19].
- **Advanced composites:** CFRP and hybrid composites can provide a weight saving of up to 56% compared with steel, and also have high specific strength and energy absorption. Nevertheless, composites can suffer a loss in strength by up to 56% if subjected to thermal events (e.g. battery fires), requiring thoughtful design and fire protection measures [18, 19].

2.5.2 Thermal Management Performance

- **Metals:** Excellent thermal conductivities and good passive heat dissipation are found for aluminium, Al/SiC MMC.
- **PCM composites:** The inclusion of PCMs in the composites uniformize temperature and minimize peak battery temperatures, leading to enhanced safety and lifetime. PCMs with high conductivity (e.g., here and in approaches based on expanded graphite) exceed, with profit, conductive low PCMs and metal-only containers [20, 21].
- **Graphene & CNT Enhanced Composites:** These additives increase thermal conductivity and improve heat dissipation, ideal for high-power battery operation [22].

2.5.3 Cost Consideration

Steel is low-cost and abundantly available; aluminium is moderately priced but more expensive than steel. MMCs like Al/SiC are cost-effective relative to CFRP. Advanced composites and CFRP are more costly due to the high costs of raw materials and processing. However, rapid-cure and automated manufacturing are reducing costs. Hybrid composites offer a balance, leveraging lower-cost metals for structural elements and composites for weight savings [18, 23].

2.5.4 Fire And Impact Resistance

Steel provides excellent fire and impact resistance; aluminium is less fire-resistant but still robust. Advanced composites require flame-retardant additives or hybridization for adequate fire resistance. Rapid-cure, self-extinguishing epoxy systems (e.g., SolvaLite® 716FR) achieve UL94 V-0 ratings and pass thermal runaway tests. Open-pore MMCs and gradient-helicoidal hybrid composites inspired by biological structures offer enhanced crash absorption and fire resistance [24, 25].

2.6 Advanced Composite Materials for Battery Pack Enclosure

The composite enclosures are being developed beyond traditional lightweighting for electric vehicle battery systems. Current research involves the manufacturing of multifunctional materials; the development of new production processes, and pioneering advanced safety systems to accommodate more and more demand for performance, strength and security. These breakthroughs are leading us from today's battery packs to the next-gen batteries that power upcoming electric vehicles (EVs) and hybrid-electric vehicles (HEVs)—the ones that will be lighter, have more energy density, better safety and a much lower cost. Recent breakthroughs have significantly enhanced the structural capabilities of composite enclosures, allowing for greater weight reduction and improved resilience [4, 26].

- CFRTP Composites Research on carbon fiber reinforced thermoplastic (CFRTP) composites has revealed the potential for substituting the conventional aluminium alloy parts. A successful project engaged in the complete replacement of all aluminium components of a car chassis through CFRTP, resulting in a 10% reduction in mass but with equivalent stiffness.
- Hybrid material systems are being explored to address the compromise between performance and cost. An interesting case is represented by the innovative structure of a light sandwich made by coupling Carbon Fibre Reinforced Polymer (CFRP) face sheets with aluminium stiffeners: it is well-suited to be employed for different vehicle parts. In addition, the fiber hybrid composites of carbon and glass fibers have been developed to improve impact strength. Although CFRP has excellent strength, Glass Fibre Reinforced Polymer (GFRP) exhibits high energy absorption performance, and by combining the two, the positive properties of both materials can be utilised.
- Advanced simulation tools are used to ensure that composite structures are maximally efficient. To the best of our knowledge, an RBDO process for the CFRP battery box was first established. It successfully resulted in a reduction of 22.14% weight with high reliability and good performance.

2.6.1 Development of Multifunctional Hybrid Nanocomposites

A significant progress has been achieved in developing multifunctional hybrid nanocomposites that are designed specifically for battery pack barrier films. One of them is a composite between CSMO supported and High-Density Polyethylene (HDPE) polymer matrix [4, 26]. This novel composite is designed to meet various needs at once:

- **Superior Moisture Barrier:** The nano-sized MgO particles act as a "getter," chemically trapping moisture. This results in an exceptionally low water-vapour transmission rate (WVTR) of less than 0.5 mg/m^2/day, a value reported to be the weakest among gas barrier films in existing literature. [26]
- **Enhanced Thermal Conductivity:** The carbon black support material for the MgO nanoparticles creates a conductive pathway for phonons, improving the composite's thermal conductivity to 1.0 $\mathrm{W/m \cdot K}$. [26]
- **Improved Mechanical Strength:** The dispersion of the CSMO filler in the HDPE matrix also leads to an increase in tensile strength, enhancing the material's mechanical robustness. [26]

2.7 Material Selection for Battery Enclosure

The choice of materials for battery enclosures plays a crucial role in determining the overall performance, safety, and cost-effectiveness of electric vehicles. Table 2.2 describes different materials and their properties. Table 2.3 describes the key findings from the materials reviewed from the literature.

Table 2.2: Material Properties for Battery Enclosures [27, 28, 29, 30, 31]

Enclosure material	**Key material properties (room temp)**	**Mechanical properties (representative)**
Low-carbon steel (e.g., AISI 1018; galvanized trays/frames)	$\rho \approx 7.85$ g/cm^3; $k \approx 52$ $\mathrm{W/m \cdot K}$	YS ≈ 370 MPa, UTS ≈ 440 MPa, $E \approx 205$ GPa.
Stainless steel (304/316L) lids/frames	$\rho \approx 8.0$ g/cm^3; $k \approx 16$ $\mathrm{W/m \cdot K}$	YS ≥ 190–205 MPa, UTS ≈ 500–700 MPa, $E \approx 193$ GPa.
Aluminum sheet/extrusions (5xxx/6xxx trays/lids; e.g., 5052-H32, 6061-T6)	$\rho \approx 2.70$ g/cm^3; k (Al alloys) ≈ 130–200 $\mathrm{W/m \cdot K}$	YS ≈ 250–276 MPa, UTS ≈ 267–310 MPa, $E \approx 69$–71 GPa. 5052-H32: YS ≈ 193 MPa, UTS ≈ 228 MPa, $E \approx 70$ GPa.
HPDC Al-Si cast trays (e.g., AlSi10MnMg / AlSi10Mg)	$\rho \approx 2.70$ g/cm^3; $k \approx 125$–140 $\mathrm{W/m \cdot K}$ @ 50°C	UTS ≈ 300 MPa, YS ≈ 100–150 MPa.

Continued on next page

Table 2.2 (continued)

Enclosure material	**Key material properties (room temp)**	**Mechanical properties (representative)**
Hybrid: Al tray + GFRP-SMC lid	GFRP-SMC: $\rho \approx 1.7–1.9$ g/cm^3; $k \approx 0.3–0.6$ W/m · K	Tensile strength $\sim$ 80–210 MPa, $E \sim 10–21$ GPa.
CFRP SMC / CFRT-P sandwich enclosures (full lids/boxes; hybrid sandwiches)	CFRP laminate: $\rho \approx 1.5–1.7$ g/cm^3; in-plane k typically $\sim$ 1–10 W/m · K	CFRP SMC & hybrids show tensile modulus $\sim$ 12–16 GPa (SMC) up to higher with continuous fiber.
Magnesium alloys (e.g., AM60B/AZ91) with advanced coatings (PEO/anodic)	$\rho \approx 1.8$ g/cm^3; $k \approx$ 50–75 W/m · K	AM60B: UTS ≈ 225–240 MPa, YS ≈ 130 MPa, $E \approx 45$ GPa (die-cast). Corrosion requires coatings; PEO shows strong improvement.

Table 2.3: Comparison of Material Classes for Battery Enclosures

Aspect	**Traditional Metals (Steel, Aluminum)**	**Metal Matrix Composites (e.g., Al/SiC)**	**Advanced Composites**
Weight Reduction	Baseline (Steel); 30–40% (Aluminum)	30–40% vs. Steel	Up to 56% vs. Steel; Potential for further reduction
Mechanical Strength	High (Steel); Moderate (Aluminum)	High, tunable	High (CFRP), but can degrade post-fire; High, but long-term durability under study
Thermal Management	Good (Al/SiC); moderate (Aluminum)	Excellent (Al/SiC, open-pore)	Enhanced with PCMs, graphene, CNTs; Superior with tunable conductivity
Fire Resistance	High (Steel); moderate (Aluminum)	Good (Al/SiC, open-pore)	Enhanced with flame retardants, hybrids; Promising, but needs further validation
Cost	Low (Steel); moderate (Aluminum)	Moderate	High (CFRP); moderate (SMC, hybrids); High (currently)
Manufacturability	Mature, scalable	Mature, scalable	Improving (rapid-cure, additive); Early stage, scalability challenges

Continued on next page

Table 2.3 (continued)

Aspect	Traditional Metals (Steel, Aluminum)	Metal Matrix Composites (e.g., Al/SiC)	Advanced Composites (CFRP, SMC, Hybrids) / Emerging Materials (MXenes, Nanocomposites)
Recyclability	Excellent	Good	Limited, but improving; Limited, under research
Environmental Impact	High (Steel); moderate (Aluminum)	Lower than steel	Lower (if recycled/renewable energy used); Potentially low, pending LCA

2.8 Challenges in Developing Advanced Battery Pack Materials

The use of polymer composites as battery pack materials presents challenges in nearly all stages of the component life, from material selection to end-of-life disposal. The key challenge, however, is one of materials and cost - lightweight performance reinforcements such as carbon fibre, for instance, are far more expensive than metal equivalents, and better manufacturing processes need to be developed for mass-market uptake.

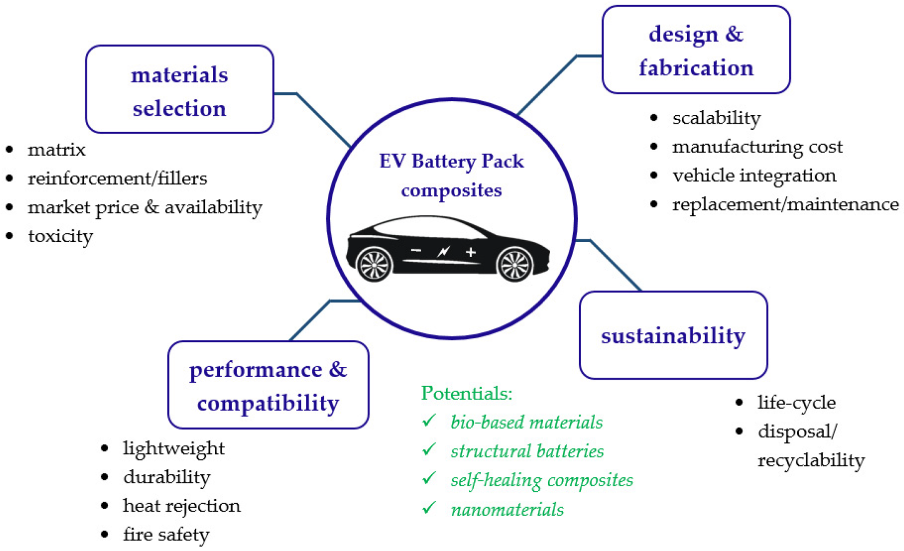

Figure 2.3: Some considerations related to the application of polymer composites for EV battery pack.

The continued availability of the required resins and fillers on the market, as well as the toxicity inherent in such chemical constituents, are additional concerns. In design and manufacturing, composites with reinforcement often rely on specialized (and usually slow) manufacturing processes like autoclave curing that are not amenable to high-throughput automotive production and therefore are expensive. In addition, the challenge of complex engineering to install a battery pack into the vehicle's chassis while also considering longevity and repairs rounds out these problems. There are also significant issues with performance and compatibility, where you can have all aspects of the design optimised for either minimum weight or maximum stiffness, potentially compromising thermal design. The low critical thermal conductivity for composites, beneficial for fire insulation, makes the rejection of heat more complex during regular operation and require a more developed internal cooling. Long-term resistance to vibration and the need to comply with tight fire, smoke, and toxicity (FST) requirements are also essential performance criteria. Finally, sustainability and lifecycle management have become one of the main barriers, since obtaining eco-efficient recycling solutions for polymer composites is a significant environmental concern. A complete lifecycle analysis must be conducted to ensure that the ecological advantages of lightweighting are not offset by the energy-intensive processes of material acquisition and product manufacturing [4].

2.9 Introduction to Pouch Cell in Electric Vehicle Battery Pack

Pouch cells are also prismatic lithium-ion rechargeable cells that pack into a flexible, multilayer laminate rather than the durable metal packing. EV packs have become attractive as they offer high packaging efficiency, low mass and good thermal contact area. Yet, they can be demanding of the encapsulant film to sufficiently block moisture/oxygen, withstand electrolyte and HF attack, deep-draw form and retain hermetic heat-seals through long life in use and under abuse. The most popular pouch film is the aluminium/plastic laminate: thin Al foil between polymer layers, bonded by adhesive/tie layer. The Al serves as a functional barrier to inhibit the penetration/escape of HO, O, and volatile solvents. At the same time, the polymers offer mechanical strength, formability, and sealability as well as chemical compatibility with cell electrolyte and electrodes [32, 33, 34, 35].

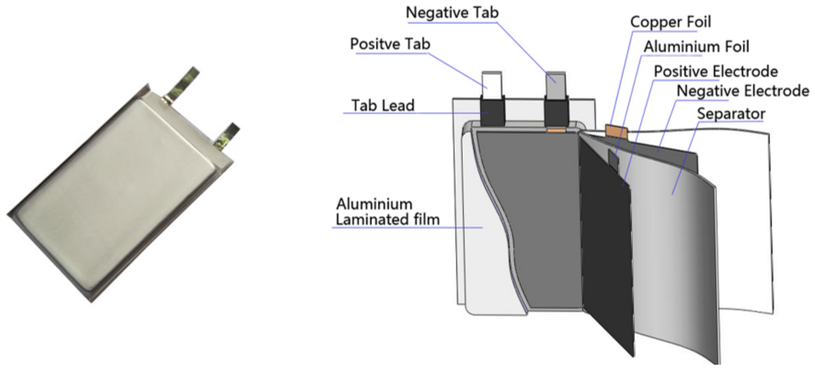

Figure 2.4: Structure of a Pouch Cell

2.9.1 Pouch Cell Laminate Architecture

The pouch cell comprises three layers: the outer layer, the barrier layer and the innermost layer. Each layers are described individually below for a better understanding.

- **Outer layer (mechanical/print/scratch protection):** outermost film is generally biaxially orientated polyethylene terephthalate ("BOPET", "PET") or polyamide ("BOPA", "nylon"). PET provides abrasion resistance, dimensional stability, and printability for traceability, while PA adds puncture resistance and drawdown in deep-formed pockets. For that reason, in most commercial stacks, the outer layer is PET/PA before the metal. During pocket-forming, the outer stack needs to distribute strain without breaking aluminium or causing interfacial de-bonding - so this work seeks to predict laminate anisotropy and draw-ratio limits for PET/PA/Al/PP constructions [32, 33]

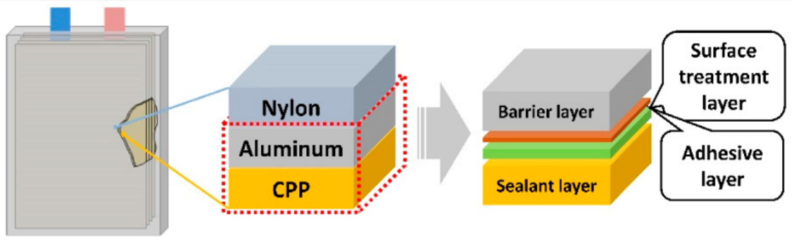

Figure 2.5: Pouch cell laminate layers

- **Barrier layer:** The primary barrier to water vapour and oxygen is a 20–40 µm thick aluminium foil (thicker for abuse resistance)—it also acts as an electromagnetic shield. Al should have no pinholes and inclusions, because even submicron defects could serve as diffusion paths and initiation sites of corrosion when exposed to electrolyte/HF. Recent research has modelled the formation and growth of pinholes from particles and rolling damage, correlating defect morphology with effective barrier loss and proposing manufacturing controls to retard evolution during forming and use [34]. Because HF is formed by electrolyte hydrolysis, aluminium surfaces are commonly conversion coated or primed and barrier durability is correlated with water-vapour transmission rate (WVTR), and stressed-ageing studies show that elevated WVTR corresponds to capacity fade in automotive-scale cells [35].
- **Inner (sealant/wet-side chemical compatibility**): The inner layer—cast polypropylene (CPP) or modified polyolefins—is selected for low-temperature heat-sealability aspects(narrow seal-window), electrolyte resistance and stress cracking resistance. The sealant must also prevent the leaching of species that poison the solid electrolyte interphase layer (SEI) and maintain its peel strength after both electrolyte soak tests and thermal cycling. Adhesive tie layers, which are often urethane-based, bond inner polymer to aluminium and outer polymers; their chemistry as well as their primer treatments govern interfacial robustness under electrolyte, heat, and mechanical loading during pack operation and crash events [36, 37].

3

Methods

This chapter describes the experimental approaches accepted to assess the performance and functional reliability of polymer–graphene oxide (GO) coatings created for electric vehicle (EV) battery pack enclosures and pouch cell laminate structures. The study concentrates on the correlation between these coatings, deposited onto different substrates such as polyamide (PA), polyethylene (PE) and carbon fabric (CF) for structural, barrier and interfacial properties related to advanced battery packaging systems.

3.1 Introduction

In the case of EV battery packs, it can be expected that packaging materials are subjected to an ongoing exposure to mechanical load, thermal cycling, humidity and chemical environment resulting from electrolyte vapours and environmental moisture. Therefore, the material layers constituting the outer, barrier and inner laminates of pouch cells or the composite enclosures of battery packs are required to have high tensile strength, low permeability, and adhesion stability between interfaces. Graphene oxide (GO) and reduced graphene oxide (rGO) have been considered as promising nano-additives because of their remarkable reinforcement effect, barrier performance and hydrophobicity. The introduction of rGO to a polymer's matrix enables its functional integration, enhancing stiffness and adhesion, while also improving resistance to water uptake/thermal degradation. Each experiment was carefully chosen to address a specific performance criterion:

- **Mechanical property testing**: Tensile test on coated polymer films (PA, PE) and coated carbon fiber fabrics to prove that the polymer-rGO coating does not degrade nor enhance tensile strength and stiffness, making it a material applicable for structural as well as flexible packaging.
- **Environmental durability**: Evaluated via a water stability (soaking) test to simulate prolonged exposure of the coating to moisture or condensation, and determine its ability to retain surface quality and exhibit resistance against water-induced degradation.
- **Interfacial reliability**: Reliability is determined by measuring the coating and substrate bonding strength as assessed from a 180° peel (adhesion) test on coated PA film and carbon fibre fabrics; this is important for multilayer laminate performance and delamination at temperature or under stress.

The experiments combined serve as a methodological platform to associate material composition and processing (rGO content, coating uniformity, substrate nature) with functional performance metrics (strength, stability and adhesion). This systematic methodology guarantees that the obtained results in the following chapter can be directly related to design parameters for high-performance pouch laminates and enclosure panels for EV battery systems.

3.2 Experimental Process for Preparation of rGO-Polymer Slurry

Preparation of coated samples was essential to ensure the uniformity, reproducibility, and reliability of subsequent mechanical and adhesion testing. In this study, a new coating system was developed, a polymer–rGO composite used as a coat upon three different substrates, polyamide (PA), polyethylene (PE), and carbon fiber fabric, to evaluate its performance on the two flexible packaging and structural laminates engineered for EV battery packages. The coating formulation was synthesized by dispersing graphene oxide powder into a polymer dispersion and chemically reducing in situ to create a stable rGO–polymer slurry. For each formulations, particular amounts of GO were mixed within the polymer matrix to produce 1, 3, and 5 wt% loadings based on polymer solids.

1. **Dispersion:** GO powder (25 mg for 1 wt%) was added to 10 mL of a polymer dispersion containing approximately 2.5 g of polymer solids.
2. **Reduction:** To this dispersion, **ascorbic acid (1 mL)** and **aqueous ammonia (1.5 mL)** were added to create basic conditions and promote chemical reduction of GO to rGO.
3. **Mixing:** The mixture was continuously stirred mechanically for **24 hours at room temperature**, resulting in a stable, homogeneous black slurry.
4. **Concentration variation:** The same procedure was repeated for **3 wt% (75 mg GO)** and **5 wt% (125 mg GO)** compositions to evaluate the influence of filler loading on mechanical and interfacial properties.

The in-situ reduction route was selected to improve dispersion stability and interfacial bonding between rGO sheets and the polymer matrix, ensuring consistency across all coating batches.

3.2.1 Substrate Preparation

All the substrates were pretreated to have transparent and homogeneous surfaces before coating:

- **PA and PE films:** Commercially available films were cut to larger size sheets, cleaned by isopropyl alcohol (IPA) and dried to remove any surface contaminants or processing oils that may interefere with the coating adhesion.
- **Carbon fiber:** Woven CF fabric pads were cut to a more easily workable size and gently air-puffed to remove any loose fibers or dust. The cloth was stretched directly onto the bed to eliminate wrinkles during the process.

Cleaning of the surface was crucial as most minor impurities may impact coating homogeneity and adhesion, both being crucial for the faithful interpretation of test results.

3.2.2 Coating Application and Drying

To a substrate, the rGO–polymer slurry was coated consistently with a applicator bar/rod, utilising a film-coating machine to obtain uniform coating thicknesses of 0.02 mm. The coating was applied just once, smoothly and uniformly at constant velocity to achieve uniform coverage.

Immediately after coating:

1. The samples were air-dried in room conditions (24 h) for the evaporation of solvent.
2. They were subsequently oven-dried at 45 °C for 5 minutes to ensure complete evaporation of solvent and film consolidation.
3. After drying, the coated substrates were gently peeled off for different substrates and rGO concentrations

The controlled drying also provided uniform coating thickness and reduced surface faults such as blistering or cracking.

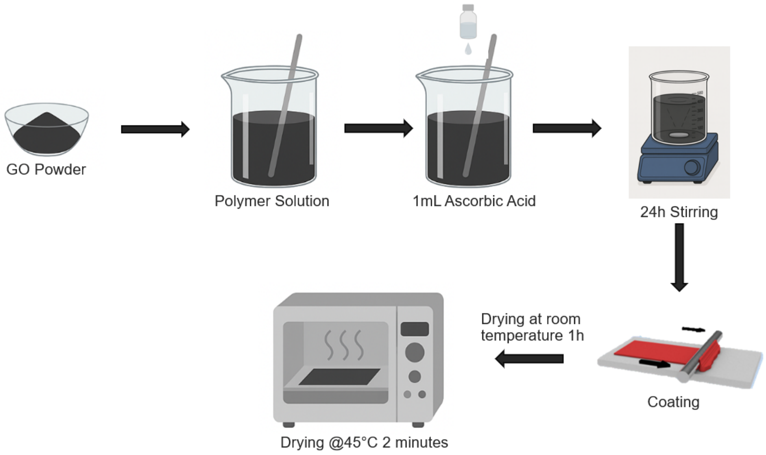

Figure 3.1: Polymer-rGO experimental process

3.2.3 Specimen Cutting and Conditioning

Table 3.1 describes the test settings and parameters used to perform the experiment.

Table 3.1: Specimen dimensions and test settings for all experimental methods

Test	Substrate	Size	Setup	Speed	Conditions
Tensile test	PA, PE, CF	9 cm × 3 cm	Universal Testing Machine (UTM) with tensile grips	5mm/min	Tested at room temperature; alignment ensured to avoid bending

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Table 3.1: (continued)

Test	**Substrate**	**Size**	**Setup**	**Speed**	**Conditions**
Adhesion (180° peel)	PA (coated)	7 cm × 2.5 cm	180° peel fixture on UTM; one side fixed, peel arm clamped	1mm/min	Constant-rate peel; peel arm bonded to coating surface; steady 180° geometry
Adhesion (180° peel)	CF (coated)	70 mm × 25 mm coupon with 25 mm peel arm	Upper grip pulls peel arm; lower rigid clamp holds CF vertically	1mm/min	True 180° peel geometry; peel arm parallel to CF surface; failure mode noted
Soak (stability)	CF only	≈7 cm × 7 cm	Coupons suspended in DI water in separate beakers	—	Fully submerged for 48 h at room temperature; kept off beaker base; post-soak surface inspection

4

Results

In this chapter, the experimental results of mechanical, adhesion and environmental stability tests carried out on polymer–rGO–coated substrates are discussed and analyzed. These results are grouped according to the test type and the used substrate -PA, PE, and CF. Each set of results is to assess the effect of rGO concentrations (1 wt%, 3 wt%, and 5 wt%) on the mechanical performance, interfacial adhesion and environmental stability of developed coating systems.

All numerical variables were input directly from the UTM (load-displacement data), while derived parameters, including tensile strength and peel load, were generated. Visual inspection was applied to check the stability and integrity of coatings at different soaking conditions. The main findings are presented in the following sections.

4.1 Mechanical Tensile Test

This chapter reports tensile results for polyethylene (PE) films coated/filled with graphene derivatives prepared by different routes. Six formulations were tested:

1. Pure polymer (PE)
2. 1 wt% polymer–GO (unreduced)
3. 1 wt% polymer–rGO (hydrazine-reduced)
4. 1 wt% polymer–rGO (ascorbic-reduced)
5. 3 wt% polymer–rGO (ascorbic-reduced)
6. 5 wt% polymer–rGO (ascorbic-reduced)

For each, engineering stress–strain curves were recorded, and a comparison overlay was generated that shows one representative curve for: pure polymer, 1 wt%, 3 wt%, and 5 wt% (ascorbic-reduced).

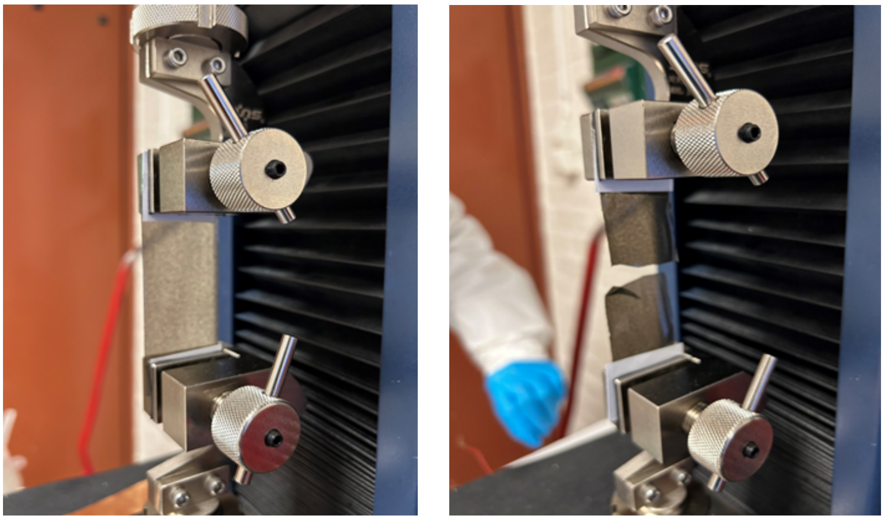

Figure 4.1: Mechanical tensile testing. Experimental setup showing the specimen mounted in the Universal Testing Machine and the loading process during tensile testing.

4.1.1 Results and Discussions for Mechanical Tensile Test

This section clearly describes the results for various samples tested.

- Pure Polymer (PP): A typical ductile behaviour with progressive strain hardening and high elongation at break was observed for the neat polymer. The maximum tensile stress was 6.2 MPa at an elongation of 200% showing a significant deformability and toughness.
- 1 wt% GO (Unreduced): Addition of 1 wt% unreduced GO caused a slight decrease in overall ductility, accompanied by a slight rise in stiffness. The highest tensile strength was 6.48 MPa at a strain of 54%. Enhancement of strength to that of pure polymer indicates some physically interacting, stress-transferring GO sheets in the matrix, with only partial interfacial bonding restricting elongation.
- 1 wt% rGO (Ascorbic Acid Reduced): The tensile strength and strain of the ascorbic acid–reduced composite were 5.65 MPa and 92%, respectively. Although of a moderate strength, the elongation was considerably larger compared to other GO-based samples, suggesting a more flexible polymer–filler interface. The relatively low degree of reduction through ascorbic acid probably maintained some oxygen groups to increase the polymer compatibility, and led to a better dispersion of the filler.
- 1 wt% rGO (Hydrazine Reduced): The hydrazine-reduced film had 5.21 MPa tensile strength and only 7.6% elongation, and exhibited brittle fracture. The high degree of reduction removed the surface oxygen functionalities, resulting in highly conducting but poorly compatible rGO sheets that agglomerated in the polymer matrix, limiting ductility and interfacial interaction.
- 3 wt% rGO (Ascorbic Reduced): When the rGO content was further increased to 3 wt% (ascorbic reduction), the tensile strength and elongation reached 5.21 MPa and up to 48%, respectively. This exhibited only a slight increase

in stiffness, which was compensated by a lower strain at break. This is an indication that at higher than 1 wt%, the graphene platelets overlap and form local strain concentrations, which hinder deformation.

- 5 wt% rGO (Ascorbic Reduced): For the 5 wt% composite, though tensile strength of 5.61MPa was obtained, a significant decrease, which declined to simply 9.2% in elongation, was also observed. The brittle nature is attributed to the aggregation of rGO sheets at high loadings, which can interrupt the matrix continuity and act as a triggering point to form cracks beforehand.

Table 4.1 summarizes the mechanical tensile testing results for different samples tested.

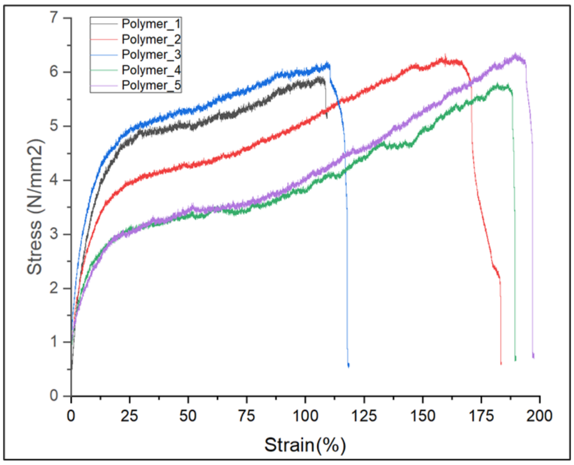

Figure 4.2: Pure Polymer- stress vs strain graph

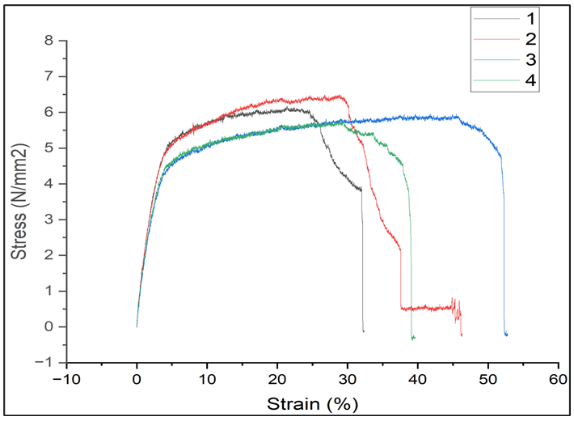

Figure 4.3: 1wt% Polymer-GO unreduced stress vs strain graph

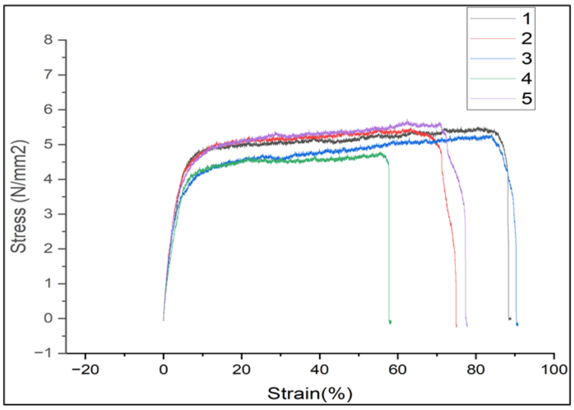

Figure 4.4: 1wt% Polymer-rGO-Ascorbic stress vs strain graph

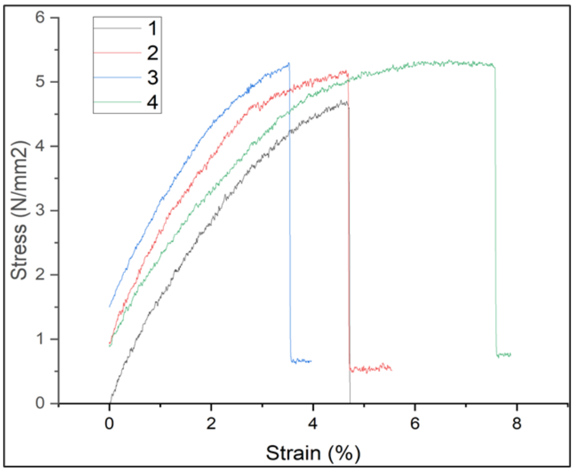

Figure 4.5: 1wt% Polymer-rGO-Hydrazine stress vs strain graph

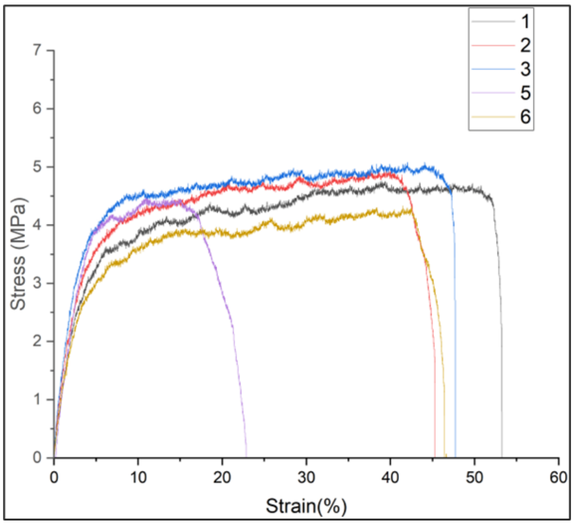

Figure 4.6: 3wt% Polymer-rGO-Ascorbic stress vs strain graph

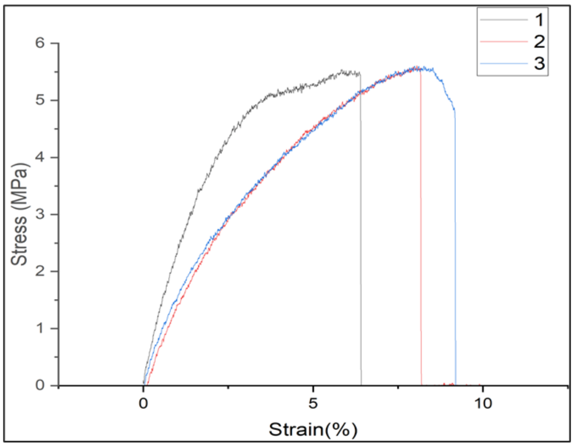

Figure 4.7: 5wt% Polymer-rGO-Ascorbic stress vs strain graph

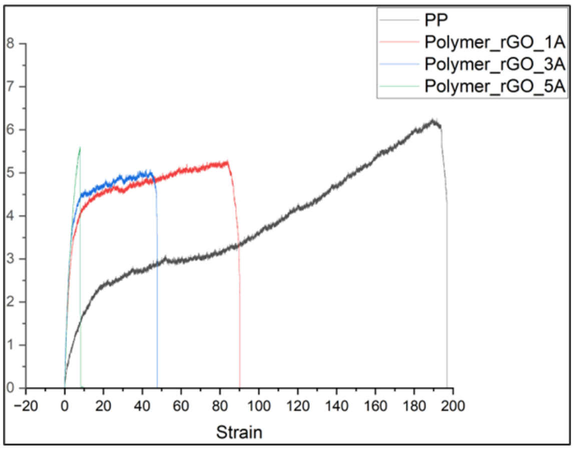

Figure 4.8: Stress vs strain comparision plot for Polymer,1wt%, 3wt% and 5wt% samples

Table 4.1: Summary of tensile properties for PE film and its graphene composites.

Sample	**Graphene reduction method**	**Max tensile strength (MPa)**	**Strain at break (%)**	**Remarks**
Pure Polymer (PE)	—	6.2	200	Highly ductile; large plastic deformation and uniform elongation before fracture.

Continued on next page

Table 4.1: (continued)

Sample	**Graphene reduction method**	**Max tensile strength (MPa)**	**Strain at break (%)**	**Remarks**
1 wt% Polymer–GO (unreduced)	None (GO)	6.48	54	Moderate strength improvement; reduced ductility due to partial interfacial bonding.
1 wt% Polymer–rGO (ascorbic acid)	Mild reduction	5.65	92	Balanced flexibility and strength; improved dispersion due to retained oxygen groups.
1 wt% Polymer–rGO (hydrazine)	Strong reduction	5.21	7.6	Brittle fracture; poor interfacial bonding from aggressive reduction and sheet aggregation.
3 wt% Polymer–rGO (ascorbic acid)	Mild reduction	5.21	48	Slight stiffness increase; reduced elongation due to partial filler agglomeration.
5 wt% Polymer–rGO (ascorbic acid)	Mild reduction	5.61	9.2	Highly brittle; excessive filler loading causes stress localization and early failure.

4.1.2 Carbon Fiber Mechanical Tensile Test

The tensile strength of carbon-fiber–polymer composites increased progressively with the addition of polymer–rGO coatings in figure 4.9. The carbon fiber coated with polymer sample exhibited an ultimate stress of about 600 MPa. Incorporation of rGO significantly enhanced load transfer efficiency between the polymer and fiber surface, with the most notable improvement observed at 3 wt%, showing approximately 22% higher tensile strength compared to the uncoated sample. At 5 wt%, although the peak stress reached the highest value, the material became brittle, displaying a sharp drop in strain due to graphene sheet agglomeration and restricted polymer chain movement. These results confirm that moderate rGO loading enhances interfacial bonding and stiffness, while excessive filler content compromises ductility.

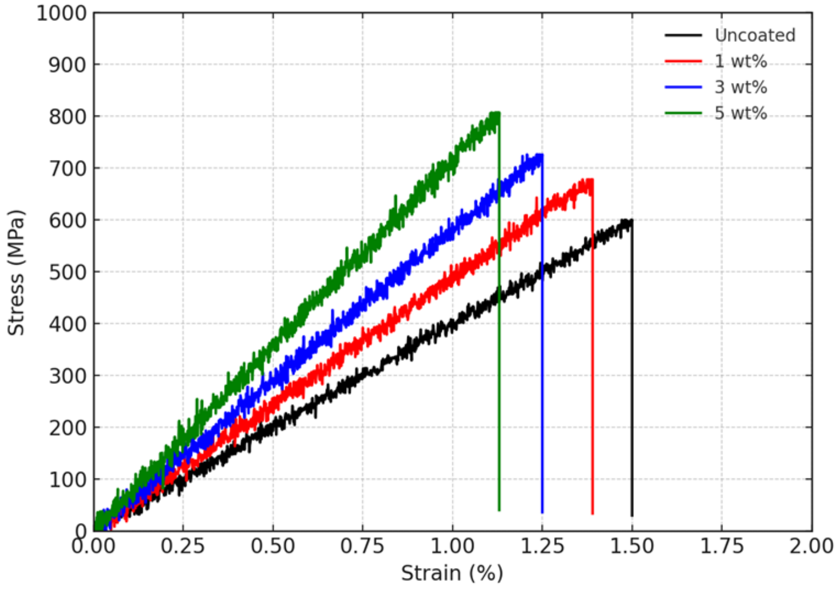

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Figure 4.9: Carbon fiber stress vs strain graph

4.2 Adhesion Test Results

Interfacial adhesion strength between the polymer-rGO coatings and the substrate materials (PA film and carbon fiber fabric) was evaluated through the 180° peel tests. The load-displacement curves reveal the interfacial stability, coating uniformity, and load transfer efficiency as a function of rGO loading.

4.2.1 Adhesion Behaviour of PA Film

For PA film, the adhesion strength initially increases with rGO loading and then decreases at higher concentrations:

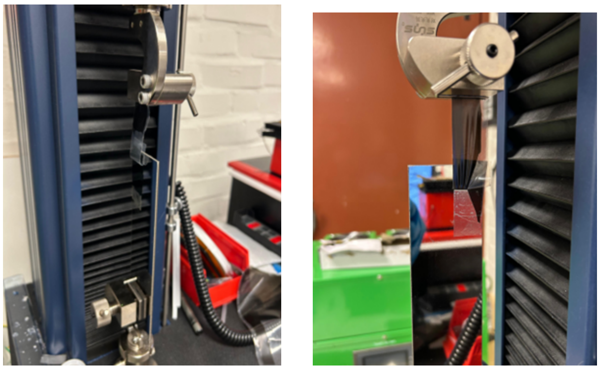

Figure 4.10: Adhesion test setup for PA film. The experimental configuration showing (left) film alignment in UTM grips and (right) peeling during load application.

- 1 wt% rGO (black line): The best initial adhesion performance, and becomes stable earlier. The load-displacement plot reveals a long plateau (9 N) with slight fluctuation, demonstrating uniform peeling and sufficient interfacial adhesion.

- 3 wt% rGO (red curve): Moderate adhesion is observed with a stable plateau (5 N) and then followed by a slight load drop; implying some degree of filler agglomeration, hence localized stress transfer.
- 5 wt% rGO (blue curve): Poor adhesion is evidenced in the graph and a force drop with fast decay due to graphene clustering and micro-void formation at the interface, leading to premature delamination.
- Polymer coating (green curve): Exhibits the lowest peel resistance and early failure, confirming the beneficial role of rGO in strengthening interfacial adhesion.

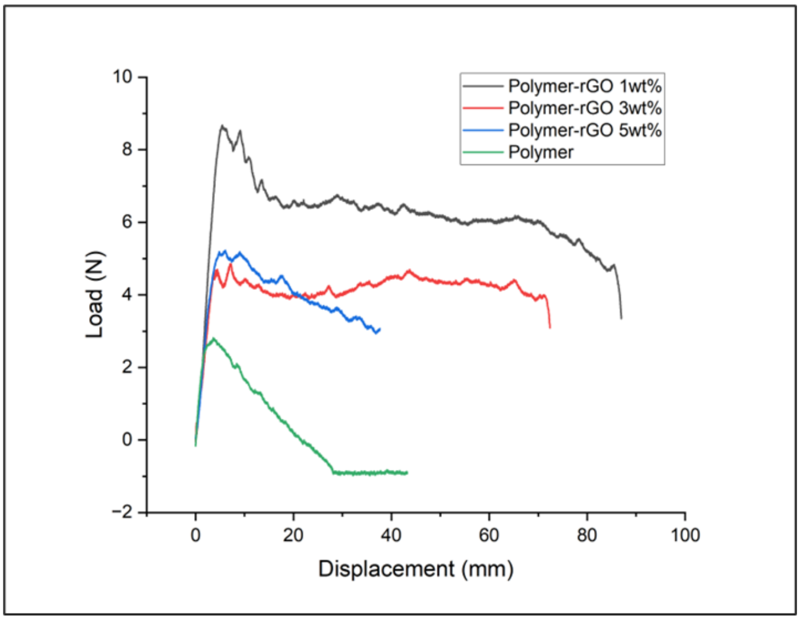

Figure 4.11: Load vs displacement graph for PA film

The results taken together suggest that 1 wt% rGO presents the optimal interfacial bonding relationship between strong adhesion and integrity in coating, while higher loading of rGO results in microstructural defects and stress concentration.

4.2.2 Adhesion Test Results – Carbon Fiber Substrate

Figure 4.13 shows the load–displacement behavior of carbon fiber samples coated with polymer–rGO composites at different loadings (1, 3, and 5 wt%). The results highlight the effect of rGO concentration on interfacial bonding and coating stability.

Figure 4.12: UTM test setup for carbon fiber adhesion testing

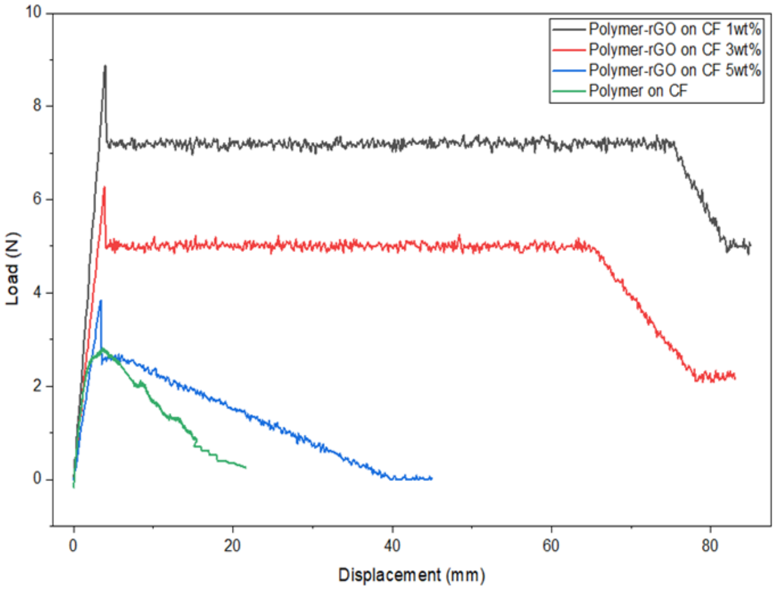

Figure 4.13: Load vs displacement graph for carbon fiber adhesion

- 1 wt% rGO (black curve): Exhibits the highest and most stable adhesion with a steady plateau around 7–7.2 N, maintaining load up to 8̃0 mm before a gradual drop. Indicates strong, stable interfacial bonding and uniform load transfer.
- 3 wt% rGO (red curve): Shows moderate adhesion strength (5̃ N plateau) with consistent peeling response. Slight load reduction beyond 6̃5 mm suggests limited dispersion and minor stress concentration.
- 5 wt% rGO (blue curve): Demonstrates low and unstable adhesion (2̃.5 N) with early decay (4̃0 mm displacement), attributed to graphene agglomeration and micro-defect formation.
- Pure polymer on CF (green curve)**:** Shows the lowest adhesion and early failure (2̃–3 N peak), confirming that the inclusion of rGO significantly enhances interfacial performance.

4.3 Stability (Soaking) Test for Carbon Fiber Samples

Coating integrity and water resistance of polymer–rGO–coated carbon fiber fabrics under humid conditions were evaluated through the stability test. The test replicates the conditions of operating in a humidity or moisture-laden environment, which can cause the coating to delaminate or for particles to be released that may impair insulation and safety. The rGO coatings on carbon fiber coupons (7×7cm) with 1 wt%, 3 wt% and 5 wt% of rGO loadings were entirely immersed in deionized (DI) water, and soaked at room temperature for 48 h. To avoid contacting the surface of the beaker, samples were suspended so that they received homogeneous irradiation. After immersion, samples were visually observed to evaluate colour changes, particles dispersion and coating adhesion. Key observations from the experiment are listed below:

- 1 wt% polymer–rGO coating: No evidence of structural breakdown or visible delamination on the rGO membrane, nor release of particles to water. The surface of the coating also showed good adhesion and stability since a uniform deposition was maintained on the fiber.
- 3 wt% polymer–rGO coating: Exhibited mild surface roughness with a faint grey colour in water, attributed to the emerged partially detached weakly-bound rGO clusters. Overall, the coating mainly remained intact.
- 5 wt% polymer–rGO coating: Exhibited noticeable dark colour of water from graphene particle dispersion, demonstrating poor stability and adhesion at high filler loading. Local debonding was observed at the surface together with a loss of coating continuity.

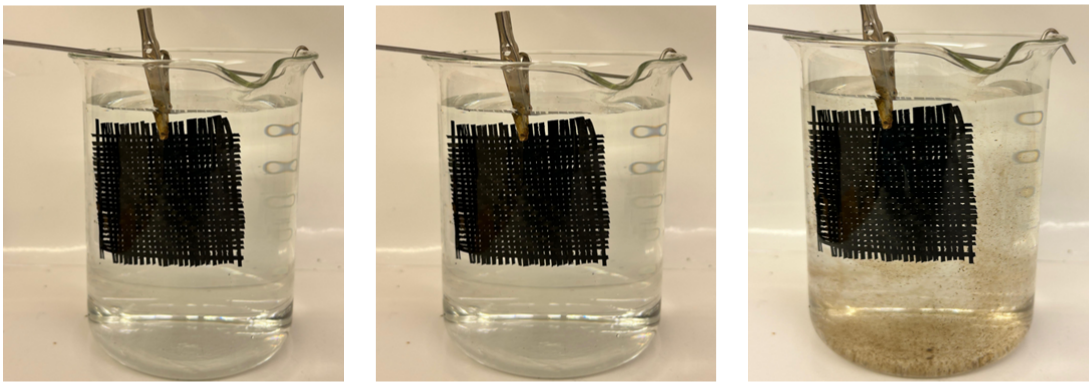

Figure 4.14: Stability (soaking) test of polymer–rGO–coated carbon fiber samples after 48 h immersion in DI water: (left) 1 wt%, (middle) 3 wt%, (right) 5 wt%.

4.4 Flexibility Evaluation of Coated Carbon Fiber

The bending capability of the polymer–rGO–coated carbon fiber fabric was investigated to explore whether the coating routine had any effect on the inherent flexibility of the substrate or not. Flexible is a prerequisite for packaging and structural components used in EV battery systems to ensure that material can form around curved surfaces and survive being handled without breaking or delaminating. Visual observation together with bending the coated samples manually indicated excellent flexibility of the polymer–rGO coating after drying. Samples were bent, twisted and folded without any sign of cracking, flaking or delamination in the coating layer.

- 1 wt% and 3 wt% coatings: Featuring smooth bending behavior, the specimen surface bore no damages and stiffening. The coat covered the fiber tow evenly and conformed to its deflection.
- 5 wt% coating: Showed a little more harsh transition, easy but still able to flex. Some slight micro-wrinkling was observed in a few locations, possibly due to rGO agglomeration-induced local thickening.

These observations suggest that the coating used creates a thin, flexible layer that is well inserted on the surface of carbon fibre, maintaining its mechanical flexibility. This kind of mechanical compliance would allow the coated material to be used on flexible or curved surfaces inside EV battery pack enclosures.

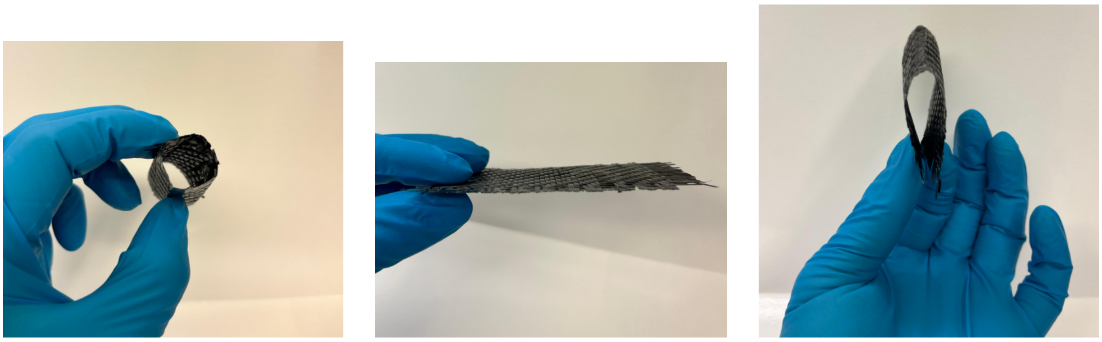

Figure 4.15: Flexibility of polymer–rGO–coated carbon fiber fabrics after drying. All samples exhibit excellent flexibility without any visible cracking or delamination.

5

Conclusion

This work has focused on the design and evaluation of polymer–graphene oxide (GO) and reduced graphene oxide (rGO) composite coatings for two key areas in EV battery systems: battery pack enclosures and pouch cell laminates. The aim was to improve the mechanical, interfacial and environmental performance of low-cost polymer- and carbon-fiber-based substrates whilst retaining flexible processing.

The work was able to systematically correlate the rGO loading, reduction chemistry with the functional performance of the coated materials. By means of the establishment of controlled experiments of tensile,adhesion and stability.

5.1 Discussion of Research Questions

The first question investigated the recent developments of lightweight and multifunctional materials for battery packaging as well as potential competition of carbon-fibre–reinforced polymer (CFRP) systems with traditional metallic cases in energy absorption, mechanical strength and ecological sustainability. The review and experimental investigation literature showed a remarkable shift in the use of materials such as aluminium or steel housings to polymer composites and hybrid systems, including CFRP, GFRP (glass fibre–reinforced polymers), and nanocomposite systems. These alternatives provide attractive solutions in superior strength-to-weight, stiffness-to-weight, corrosion resistance and damping over steel that have potential for mass reduction and improved energy conversion efficiency of electric vehicles. The performance per unit weight of CFRP systems was higher than that of metal covers, and the hole corrosion was avoided. Cost, thermal conductivity, and the presence of a recycling ecosystem continue to favour metals; however, overall sustainability and life cycle advantages achieved with CFRP (alongside recycled fibres and thermoplastic matrices) position them as a strong contender for a future battery enclosure.

The second research question concerned the contribution of graphene–polymer composite coatings on carbon fibre and polyamide (PA), and polyethylene (PE) films to the mechanical strength, adhesion, and stability of battery packaging materials compared to state-of-the-art aluminium-based laminates. The results of the experiments showed that the addition of rGO to the polymer matrix led to significant improvements in the interface and mechanical properties of coatings. The tensile test performed on the PE-based film demonstrated that 1 wt% polymer–rGO (ascorbic acid–reduced) coating struck the best balance between strength and ductility, at higher filler loadings (3 wt% and 5 wt%), stiffness was observed to increase significantly with a large magnitude of brittleness due to agglomeration of particles. Adhesion tests on PA film and carbon fibre substrates revealed a consistent trend: 1 wt% rGO showed the maximum peel force, having reached a saturation level of 7 N in carbon fibres, whereas an increase in filler content led to less stable adhesion. The 48-hour water soak test confirmed that lower rGO content coatings remained stable without particle release, while higher loadings led to visible graphene detachment. This work demonstrates that carefully designed graphene-based polymer coatings may indeed strengthen polymeric and composite substrates, enhancing adhesion and environmental resistance, respectively, at far lower weight than metallic laminates.

The third research question investigated whether metal-free packaging laminates of graphene–polymer–coated PA/PE films could deliver sufficient barrier and mechanical properties for pouch cell applications, as well as lightweight and sustainable properties. From these results, it is revealed that the laminates show good mechanical and interfacial performance and maintain flexibility after drying, which would be essential for handling, sealing and forming in pouch cells. Direct measurement of water vapour or oxygen transmission rates was not carried out in this study; however, the known tortuous diffusion path presented by layered rGO indicates that the gas and moisture barrier properties are significantly increased when compared with uncoated polymers. The 1 wt% graphene-–polymer laminate was distinctly efficient in keeping adhesion and flexibility, but higher loadings adversely affected the stability and brittleness. Thus, metal-free laminates with rational rGO loadings have the potential to serve as lightweight substitutes for aluminium-based pouch cell that are resistant against corrosion while being mechanically reinforced and potentially environmentally friendly through sustainable synthesis and low-temperature processing.

Overall, the integrated outcomes from this research prove that the 1 wt% polymer-rGO (ascorbic acid-reduced) coatings give the most favourable combo of durability, sticking, and resistance to environmental factors. The coatings enable the creation of multifunctional, lightweight, and corrosion-resistant materials, making them applicable in the manufacturing of both EV battery enclosures and pouch cell laminates.

5.2 Future Work

Although this research offers fundamental understanding of polymer–rGO–coated materials for EVs, there are directions for modernization and industrial translation:

1. Advanced charecterization: conduct microscopic (SEM, AFM) and spectroscopic (FTIR, Raman) analyses to understand coating morphology, interfacial bonding, and rGO dispersion mechanisms. Perform thermal conductivity and barrier permeability tests (WVTR/OTR) to quantify multifunctional performance.
2. Optimization of coating formulation: investigate bio-based or thermoplastic polymer matrices for higher recyclability and mechanical strength. Also, explore hybrid nanofillers (rGO + boron nitride, silica, or nanoclay) to achieve flame retardancy and enhanced thermal management.

3. Scalability and industrial integration: further develop the coating process towards roll-to-roll or spray deposition systems for production of large-area composite panels. Assess uniformity and adhesion under automated industry conditions and compare to commercial coatings standards.
4. Application Testing: integrate coated carbon fiber panels within prototype battery enclosures to test crash durability and vibration resistance. Coat pouch cell laminate prototypes with polymer–rGO to test its ability to heat-seal, resist swelling and barrier performance during the intended use.
5. Sustainability and LCA: conduct LCA to compare polymer–rGO composites in aluminium or steel enclosures concerning the amount of energy savings, emissions reduction, and recyclability. Assess the economic viability of up-scaling green reduction and coating techniques for industrial manufacture.

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