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Adhesives, Sealants, and Heat Transfer Materials in Battery Systems:
A Primer on Materials, Applications, and End-Use Performance Requirements

RATIONALE

Five-Year Review. Should be a limited number of revisions.

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1. SCOPE

This SAE Information Report introduces key concepts and properties of adhesives, sealants, and heat transfer materials (HTMs) and the roles they serve in present-day battery systems applications. The basic chemistry and properties of the three types of materials are summarized along with important health and environmental information. Relevant material dispense methodologies and equipment for material dispensing is reviewed. A series of representative battery applications examples employing adhesives, sealants, and HTMs is also provided with particular attention given to end-use performance.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (U.S. and Canada only) or +1 724-776-4970 (outside U.S. and Canada), www.sae.org.

SAE J1715/2 Battery Terminology

SAE J1797 Recommended Practice for Packaging of Electric Vehicle Battery Modules

SAE J2289 Electric-Drive Battery Pack System: Functional Guidelines

SAE J3073 Battery Thermal Management

Hayashida, A., and Kakigi, T., "Robust Design on Adhesive Material and Bonding Process for Automotive Battery Pack," SAE Technical Paper 2019-01-0160, 2019, <https://doi.org/10.4271/2019-01-0160>.

2.1.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9500, www.astm.org.

ASTM D256 Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics

ASTM D395 Standard Test Methods for Rubber Property - Compression Set

ASTM D429 Standard Test Methods for Rubber Property - Adhesion to Rigid Substrates

ASTM D454 Standard Test Method for Rubber Deterioration by Heat and Air Pressure

ASTM D471 Standard Test Method for Rubber Property - Effect of Liquids

ASTM D573 Standard Test Method for Rubber - Deterioration in an Air Oven

ASTM D575 Standard Test Methods for Rubber Properties in Compression

ASTM D638 Standard Test Method for Tensile Properties of Plastics

ASTM D1002 Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)

ASTM D1338 Standard Practice for Working Life of Liquid or Paste Adhesives by Consistency and Bond Strength

ASTM D1415 Standard Test Method for Rubber Property - International Hardness

ASTM D1875	Standard Test Method for Density of Adhesives in Fluid Form
ASTM D1876	Standard Test Method for Peel Resistance of Adhesives (T-Peel Test)
ASTM D2196	Standard Test Methods for Rheological Properties of Non-Newtonian Materials by Rotational Viscometer
ASTM D2202	Standard Test Method for Slump of Sealants
ASTM D2240	Standard Test Method for Rubber Property - Durometer Hardness
ASTM D2247	Standard Practice for Testing Water Resistance of Coatings in 100% Relative Humidity
ASTM D2556	Standard Test Method for Apparent Viscosity of Adhesives Having Shear-Rate-Dependent Flow Properties Using Rotational Viscometry
ASTM D2739	Standard Test Method for Volume Resistivity of Conductive Adhesives
ASTM D2918	Standard Test Method for Durability Assessment of Adhesive Joints Stressed in Peel
ASTM D2919	Standard Test Method for Determining Durability of Adhesive Joints Stressed in Shear by Tension Loading
ASTM D3166	Standard Test Method for Fatigue Properties of Adhesives in Shear by Tension Loading (Metal/Metal)
ASTM D3330	Standard Test Method for Peel Adhesion of Pressure-Sensitive Tape
ASTM D3418	Standard Test Method for Transition Temperatures and Enthalpies of Fusion and Crystallization of Polymers by Differential Scanning Calorimetry
ASTM D3762	Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)
ASTM D3983	Standard Test Method for Measuring Strength and Shear Modulus of Nonrigid Adhesives by the Thick-Adherend Tensile-Lap Specimen
ASTM D5470	Standard Test Method for Thermal Transmission Properties of Thermally Conductive Electrical Insulation Materials
ASTM D5573	Standard Practice for Classifying Failure Modes in Fiber-Reinforced-Plastic (FRP) Joints
ASTM D7836	Standard Test Methods for Measurement of Yield Stress of Paints, Inks and Related Liquid Materials
ASTM E1461	Standard Test Method for Thermal Diffusivity by the Flash Method
ASTM E2041	Standard Test Method for Estimating Kinetic Parameters by Differential Scanning Calorimeter Using the Borchardt and Daniels Method
ASTM G75	Standard Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)

2.1.3 European Standard (EN) Publications

Copies of these documents are available online at www.en-standard.eu.

EN 60529 Degrees of protection provided by enclosures (IP Code)

2.1.4 ISO Publications

Copies of these documents are available online at www.iso.org/store.

ISO 48-4	Rubber, vulcanized or thermoplastic - Determination of hardness - Part 4: Indentation hardness by durometer method (Shore hardness)
ISO 48-5	Rubber, vulcanized or thermoplastic - Determination of hardness - Part 5: Indentation hardness by IRHD pocket meter method
ISO 188	Rubber, vulcanized or thermoplastic - Accelerated ageing and heat resistance tests
ISO 813	Rubber, vulcanized or thermoplastic - Determination of adhesion to a rigid substrate - 90 degree peel method
ISO 814	Rubber, vulcanized or thermoplastic - Determination of adhesion to metal - Two-plate method
ISO 815	Rubber, vulcanized or thermoplastic - Determination of compression set
ISO 1817	Rubber, vulcanized or thermoplastic - Determination of the effect of liquids
ISO 5660-1	Reaction-to-fire tests - Heat release, smoke production and mass loss rate - Part 1: Heat release rate (cone calorimeter method) and smoke production rate (dynamic measurement)
ISO 5893	Rubber and plastics test equipment - Tensile, flexural and compression types (constant rate of traverse) - Specification
ISO 7743	Rubber, vulcanized or thermoplastic - Determination of compression stress-strain properties
ISO 9142	Adhesives - Guide to the selection of standard laboratory ageing conditions for testing bonded joints
ISO 9227	Corrosion tests in artificial atmospheres - Salt spray tests
ISO 10364	Structural adhesives - Determination of the pot life (working life) of multi-component adhesives
ISO 11343	Adhesives - Determination of dynamic resistance to cleavage of high-strength adhesive bonds under impact conditions - Wedge impact method
ISO 11357-3	Plastics - Differential scanning calorimetry (DSC) - Part 3: Determination of temperature and enthalpy of melting and crystallization
ISO 22007-2	Plastics - Determination of thermal conductivity and thermal diffusivity - Part 2: Transient plane heat source (hot disc) method

2.1.5 UL Publications

Available from UL, 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: 847-272-8800, www.ul.com.

UL 94	Tests for Flammability of Plastic Materials for Parts in Devices and Appliances
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2.1.6 Other Publications

- [1] Allcock, H.R., Mark, J.E. and Lampe, F.W. (2003). *Contemporary Polymer Chemistry* (3rd ed.) Prentice Hall.
- [2] McCrum, N.G., Buckley, C.P., and Bucknall, C.B. (reprinted 2011). *Principles of Polymer Engineering* (2nd ed.). Oxford University Press.
- [3] Hartshorn, S.R. (Ed.). (1986). *Structural Adhesives: Chemistry and Technology*. Springer.
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- [5] Mittal, K.L. and Pizzi, A. (2009). *Handbook of sealant technology*. CRC Press.
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- [7] Sarvar, F., Whalley, D.C., and Conway, P.P. (2006, September). *Thermal interface materials - A review of the state of the art* [Conference paper]. 1st Electronics System-Integration Technology Conference.
- [8] Sorenson, M. (2014). Automation in the Metering, Mixing, and Dispensing of Adhesives and Sealants. *Adhesives and Sealants Magazine*.
- [9] Excerpt from "BMW i3 Battery Production" YouTube video, <https://www.youtube.com/watch?v=iiJsKza5CF4>, September 12, 2013.
- [10] Excerpt from "Nissan EV battery production at Sunderland, UK" YouTube video, <https://www.youtube.com/watch?v=hihJG7Weln8>, January 20, 2016.
- [11] Excerpt from "How It's Made: Mercedes-Benz Battery Production Plant Assembly Line" YouTube video, <https://www.youtube.com/watch?v=iBhFTJ-aJbE>, May 15, 2017.
- [12] Tennessen, P.T., Weintraub, J.C., and Hermann, W.A. (2014) "Extruded and ribbed thermal interface for use with a battery cooling system." U.S. Patent 8758924.

3. INTRODUCTION

Over the last several decades, the world's strong dependence on fossil fuels and the corresponding negative impacts of carbon dioxide emissions on the environment have heightened the need for cleaner energy technologies for mobility applications. Moreover, recent government mandates on emissions coupled with swift advancements in battery technology have led to rapid growth and introduction of electric vehicles (EVs). Manufacturers along the entire electric mobility value chain now face the daunting technical challenge to quickly create vehicles that match the reliability and performance of the 100-year evolution of internal combustion engine (ICE) propelled vehicles. It is imperative that experts in the electrification community come together to share technical information to help educate and develop globally accepted standards for the public. This SAE Information Report provides an introduction to the use of adhesives, sealants, and HTMs for battery systems.

Adhesives, sealants, and HTMs play a pivotal role in the assembly and performance of battery systems for mobility applications. Proper selection of such materials from the cell to the pack level is vital for achieving high-throughput manufacturing and for effectively and safely managing mechanical, environmental, and thermal loads in the end product. Moreover, serviceability and global regulatory requirements must be considered during the selection process. In order to facilitate this process and the greater advancement of battery-propelled vehicles, a concise body of knowledge pertaining to this subject is warranted. The purpose of this information report is to introduce the basic concepts and properties of adhesives, sealants, and HTMs and the roles they serve in battery systems. Specifically, Section 4 provides a brief overview of the common chemistries used to formulate adhesives, sealants, and HTMs for battery systems. Relative performance characteristics coupled with handling, environmental, and recyclability aspects are highlighted. Sections 5 through 7 provide a deeper review of the three types of products. Material definitions are provided along with details of subclasses, noteworthy formulation constituents, and pertinent industrially accepted test methods.

Section 8 is devoted to educating the reader on how adhesives, sealants, and HTMs are dispensed in a manufacturing setting. General guidance is given as to what type of dispense equipment is most appropriate for a given rheology and product type. Section 9 provides a series of representative examples of battery applications in which adhesives, sealants, and HTMs are used. Specific attention is given to the construction of various applications, such as battery cells, modules, packs, and enclosures, and how the materials facilitate certain end-use performance properties. The topics of product safety, e.g., fire retardancy, impact resistance, etc., are also briefly addressed. Lastly, the report contains a useful appendix with a summary of the most relevant test methodologies for these materials.

4. OVERVIEW OF COMMON CHEMISTRIES

This section provides a brief overview of the common chemistries used to formulate adhesives, sealants, and HTMs for battery systems. Focus is on the matrix chemistry of the various product forms. Information on other important components (e.g., fillers, specialty additives, etc.) is discussed in general. Additional information on constituents unique to adhesives, sealants, or HTMs is included in Sections 5, 6, and 7, respectively.

4.1 Background on Chemistries

Adhesives, sealants, and HTMs in their simplest form are comprised of a heterogeneous mixture of solid filler particles within a continuous matrix. The matrix heavily dictates dispensing and end-use performance and is often used to provide distinction between different product types. Fillers modify the performance of the composite and can affect both processing and final material properties.

Matrices are primarily comprised of either thermoplastic or thermosetting polymers. Thermoplastics are a class of polymeric materials of moderate to high molecular weight that behave as solids at ambient temperature and can be softened via heating to give a material that will flow. The molecular chains of these polymers do not cross-link and remain essentially unchanged after repeated processing. In contrast, thermosets are generally liquids or pastes at ambient temperature, undergo a chemical reaction, commonly termed cure, to give a solid material that cannot be directly reprocessed. Figure 1 shows a plot of the polymer modulus or stiffness on a log scale versus temperature that illustrates the differences in behavior between thermoplastics and thermosets. Unlike thermoplastics, thermosetting polymers maintain a finite modulus at high temperatures (i.e., greater than the melting temperature, T_m , of thermoplastics), which is the result of their cross-linked network.

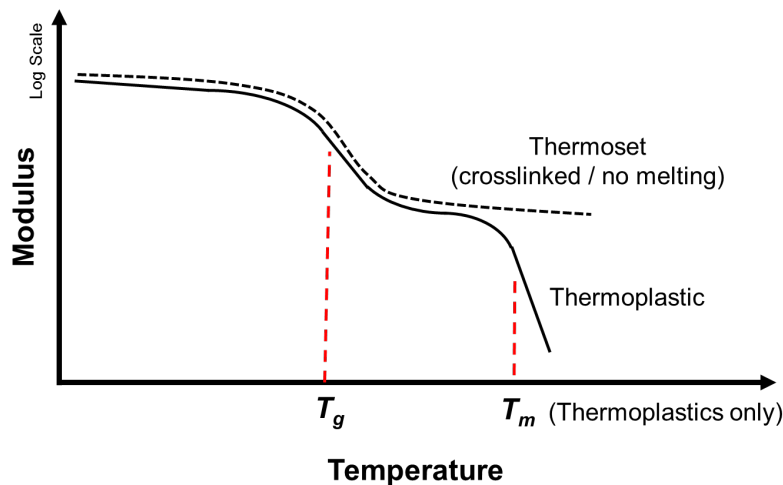


Figure 1 - Conceptual DMA curve (modulus - log scale versus temperature) showing the glass transition, T_g (thermosets, dashed line; and thermoplastics, solid line) and the melt behavior of amorphous thermoplastics

Each of these classes of polymers has advantages and disadvantages for use in battery systems. Because thermoplastic polymers are unchanged during processing, they enjoy the benefit of recyclability, yielding a positive sustainability footprint. However, the relatively high temperature required for processing thermoplastics can be prohibitive in battery applications, especially when used near batteries that cannot exceed 60 to 70 °C. Thermosets can cure at ambient or mildly elevated temperature and generally exhibit greater dimensional stability, heat resistance under load, and best-in-class chemical resistance, but the cured materials are generally not recyclable. However, softer thermosets may be reworkable, allowing for disassembly and recycling or reuse of other components. Additional features of thermoplastics and thermosets are discussed below. For an even deeper discussion of the chemistry and behavior of these materials, the reader is directed to references herein [1][2].

4.2 Thermoplastic Polymers

As noted above, thermoplastics are generally solids that flow reversibly at elevated temperatures, allowing them to be processed into various shapes. Thermoplastics can be further categorized according to their morphological state, where these polymers exhibit either amorphous or semi-crystalline microstructure. The principle difference between amorphous and semi-crystalline polymers is how they soften with temperature, which is highlighted in Figure 1. The softening point where the polymer changes phase from a glass to a rubber (commonly called the glass transition temperature, T_g) is indicative of amorphous thermoplastic materials. Upon further heating, the system will soften to the point where it can flow under pressure to fill various molds or create other geometries. These attributes are very different from semi-crystalline thermoplastics that exhibit a continuum of amorphous polymer that harbors discrete areas of highly organized crystalline polymer (hence the term “semi-crystalline”). Semi-crystalline thermoplastics are categorized by having both a glass transition temperature, T_g , and a crystalline melting point, T_m . Due to these discrete crystalline phases, a semi-crystalline material can typically withstand aggressive environments and yield higher thermal performance.

Thermoplastic materials are routinely modified via melt blending with other polymers, rubbers, fillers, and/or fibrous reinforcement. The resultant products can be formulated to exhibit high toughness, increased mechanical strength, and tremendous improvement in stiffness. It is common to formulate thermoplastics using these modifiers to produce pelletized products that can be stored for extremely long periods with no deleterious effects. These pellets, when softened (amorphous thermoplastics) or melted (semi-crystalline thermoplastics) via heat application, will flow under pressure to achieve shaped articles that have a desirable balance of mechanical performance attributes. Some examples of thermoplastics used in battery systems are liquid grease HTMs, hot melt adhesives, and low molecular weight olefins.

4.3 Thermosetting Polymers

Thermosetting polymers, because they can be processed and applied at room temperature, are the most frequently encountered class of organic matrices in battery adhesives, sealants, and HTMs. Such materials in their initial, pre-dispensed state consist of reactive liquid small molecules, e.g., monomers or low molecular weight polymers. The low molecular weight pre-cured molecules afford low-viscosity formulations that readily flow, which is necessary for high-throughput dispensing during manufacturing operations. Once applied, the molecules react to form a solid, three-dimensional cross-linked network. The network provides the end-use performance properties such as modulus, strength, or vibration damping characteristics. While thermosetting polymers generally will exhibit a glass transition from a rigid to a rubbery state, they will not exhibit melting or softening to the point of flow because of the cross-linked network.

Thermosetting products are supplied either as one-part (1K) or two-part (2K) mixtures, with the former cross-linking via the use of high temperatures, chemical triggers such as moisture, or ultraviolet (UV) radiation. More often, products are supplied as 2K materials in which each part contains separate monomers (frequently referred to as “resin” and “hardener” or A- and B-sides) that will react with one another upon mixing. Reactions often occur at room temperature but can be accelerated at higher temperatures.

Several common classes of cure mechanisms for thermosetting materials are worth noting. Condensation polymerization involves the reaction of two reactive species to form a polymer and a low molecular weight by-product. The extent of reaction is governed by the removal of the by-product, often via diffusion. In large masses or confined spaces, the requirement for by-products to diffuse away can create issues with curing or void formation inside the material. Addition polymerization involves the reaction of two species with no by-product. Materials that contain no solvents and that cure via addition polymerization are sometimes referred to as “100% solids” formulations. Radical cure involves the use of free radicals to react with unsaturated monomers. Free radicals can be generated by an oxidizing agent that is activated chemically by heat or by UV radiation. Applications for UV cure materials are more limited because of the requirement that the UV light has access to the bulk of the polymer for complete cure. Each of the chemistries is capable of cure at or near room temperature, which is often a key requirement for battery systems.

The final properties of battery system materials are ultimately dictated by the type of backbone chemistry of the thermosetting or thermoplastic polymer. Tables 1 and 2 summarize the most common chemistries used to formulate adhesives, sealants, and HTMs, along with their relative performance attributes and chemical structures, respectively.

Table 1 - Relative property comparisons between silicone, urethane, acrylate, epoxy, and silyl modified polymer (SMP) materials

Properties	Silicone*	Urethane*	Acrylate*	Epoxy*	SMP*
Tensile strength	Low	High to Medium	High to Medium	High	Low to Medium
Young's modulus	Low	Medium	Medium to High	High	Low
Elongation at break	High	Medium	Medium	Low	High
Adhesion to substrates	Low	Selective	Selective	Selective	High
Cure shrinkage	Low to Medium	Low	Medium to High	Low	Low to Medium
Compression set resistance	High	High to Medium	Medium	Low	Medium
Thermal resistance	High	Medium	Medium	High	Low to Medium
Curing rate	Slow to Moderate	Moderate	Moderate to Fast	Slow to Moderate	Slow to Moderate
Heat and humidity resistance	High	Medium	Medium	Medium to High	Medium
Glass transition temperature, T_g	Low	Low to Medium	Medium	High	Low
Coefficient of thermal expansion, CTE	High	Medium	Medium	Low	High
Hardness	Low	Low to Medium	Medium	High	Low
Chemical resistance (oils, etc.)	Low	Medium	Medium	High	Medium

* Relative performance may vary considerably depending upon the selection of raw ingredients and the specific curing mechanism used for each of the common classes.

Table 2 - Chemical structures of the most common organic matrices used in adhesives, sealants, and HTMs for battery systems.

Matrix Chemistry Class	Associated Chemical Structure
Silicone	$\left(\begin{array}{c} \text{CH}_3 \\ \\ \text{—Si—O—} \\ \\ \text{CH}_3 \end{array} \right)_n$
Polyurethane	$\text{—NH—}\overset{\text{O}}{\parallel}\text{C—O—}$
Acrylate	$\text{CH}_2=\text{CH—}\overset{\text{O}}{\parallel}\text{C—OR}$
Epoxy	$\begin{array}{c} \text{CH}_2\text{—CH—R} \\ \quad \\ \text{O} \end{array}$
Silyl modified polymers (SMP)	$\begin{array}{c} \text{OCH}_3 \text{ or } \text{CH}_3 \\ \\ \text{H}_3\text{C—Si—R—} \\ \\ \text{OCH}_3 \end{array}$



Silicones, also termed polysiloxanes, have very low T_g so that they are in their rubbery, low-modulus state under most operating conditions, making them good for low-stress and/or vibration-suppressing interface materials. They have high-temperature and moisture stability but relatively low resistance to organic chemicals, exposure to which frequently will swell and weaken the polymer. The silicone monomers have relatively low viscosity along with low surface tension, which is good for wetting substrates and various fillers. Their adhesion to most substrates is relatively low, requiring use of adhesion promoters in the formulation of primers for the bonding surfaces. Silicones cure by several mechanisms, offering useful options as 1K or 2K liquids that can be formulated for a variety of applications. Room temperature vulcanization (RTV) curing generally uses a tin catalyst and atmospheric water that diffuses into the 1K-applied material, which then cross-links to form a network. Addition cure generally involves a hydrosilylation reaction between a vinyl-functional silicone and hydride-functional silicone in the presence of a platinum catalyst. Because of the reactivity, these types of silicone generally are supplied in the form of a 2K (i.e., resin and hardener).

Urethanes, also termed polyurethanes (PU), offer a wide range of hardness and elasticity coupled with high toughness, which makes them suitable for many types of applications, such as adhesives, coatings, and encapsulants. Thermosetting PUs can be 1K moisture-cure systems or 2K systems that do not require moisture, and they even are found in thermoplastic form, known as thermoplastic urethanes (TPUs). Two-part thermosetting urethanes cure via an addition reaction between isocyanate- and hydroxyl-functional molecules in the presence of a catalyst. A wide variety of oligomers, monomers, and catalysts are available, yielding the wide range of mechanical properties observed. Thermosetting PUs also generally have good adhesion to a variety of substrates, and the harder versions are more chemically and moisture resistant than the softer versions. The thermal resistance of PUs is much less than for silicones, but given the mild thermal limits of the battery system components, this is not usually a concern in battery applications.

Acrylate polymers are another prevalent class of polymer that offers a good combination of strength and flexibility over a range of operating temperatures. They are particularly useful as adhesives and coatings. Fine control of mechanical properties is possible by using wide range of monomers and oligomers. Products may consist of 1K UV curable or 2K systems. One-part UV systems typically consist of monomers, oligomers, additives, and photoinitiators that can react within a few seconds when exposed to UV light. Note, however, the end application must not block the UV light from hitting the material to be cured. Generally, transparent and semi-transparent substrates let enough light pass through to initiate UV cure, but dual-cure systems involving both light and heat may be required when light cannot reach parts of the bond line. In the case of two-part acrylates, the individual sides are mixed and cured at room temperature, which is also relatively rapid compared to addition chemistries due to the free-radical polymerization mechanism. In certain situations, the cured acrylate may be subjected to a post-bake to further enhance performance. Because of the wide selection of acrylate monomers and oligomers, 2K acrylates can be formulated to optimize desired physical properties.

Epoxyes, or epoxy-based polymers, are another common and versatile class of thermosetting chemistries. Epoxyes offer high strength, excellent chemical and heat resistance, and good adhesion to a variety of substrates. They are generally high- T_g materials with high modulus and high tensile strength but low elasticity. Epoxyes are typically supplied as 2K systems that cure at room temperature or with moderate heat, but they are also available in 1K heat-cured systems. Epoxy resins in 2K systems are blended with a variety of hardeners, usually based on amines, amides, and/or amidoamines. One-part systems combine the epoxy resin with latent hardeners that are stable at room temperature but rapidly cure at relatively high temperatures. Given the large abundance and variety of epoxy resins and hardeners, it is possible to achieve a wide variety of properties in both the uncured and cured state.

Silane Modified Polymers (SMPs), also known as silyl-terminated or silane-terminated polymers, are a class of materials that combine the mechanical strength of polyurethane with the weather resistance and flexibility of silicone. These polymers are characterized by a polyether or polyurethane backbone that ends with reactive silane groups. When exposed to moisture, the silane groups undergo hydrolysis and condensation reactions, forming durable siloxane bonds. This moisture-curing mechanism allows SMPs to transition from a liquid or gel state into a solid elastomer without the need for solvents or isocyanates. As a result, SMPs are widely used in environmentally friendly adhesives and sealants. In automotive, they are often used in place of silicones that might affect paint lines. Key properties include: excellent adhesion to a wide range of substrates, high elasticity and flexibility, resistance to UV radiation, temperature extremes, and microbial growth and low VOC emissions.

4.4 Other Ingredients in Battery System Materials

In addition to the organic matrix, numerous other ingredients are often present in adhesives, sealants, and HTMs. Table 3 lists some of the most common ones and the roles they play. Explicit examples of secondary ingredients are highlighted in Sections 5, 6, and 7.

Table 3 - Examples of common ingredients in adhesive, sealant, and HTM formulations

Ingredient	Role
Reinforcing fillers	Enhance mechanical properties (e.g., modulus, strength, toughness, thermal expansion)
Functional fillers	Provide a specific desired property (e.g., thermal or electrical conductivity)
Cost-reducing fillers	Take up volume in the material to significantly reduce cost
Rheological modifiers	Adjust flow properties to meet dispensing requirements and improve shelf life
Pigments	Provide color/contrast between the formulation and the substrate and/or between the A- and B-sides
Fire retardants	Achieve fire-retardant and flame-resistance requirements
Adhesion promoters	Boost adhesion to a specific substrate
Initiators	Initiate a chemical reaction, often in response to heat or radiation
Accelerators	Speed up reaction of a thermosetting resin and are consumed during the process
Catalysts	Speed up reaction of a thermosetting resin and are not consumed during the process
Inhibitors	Slow down the rate of reaction of a thermosetting resin

Rheological modifiers are liquids or solids that are added, usually in small amounts, to adjust the flow properties of the material to optimize its dispense in a particular application. Some applications may require a material that flows easily and self-levels, whereas others may require dispensing a bead of material that does not sag or slump after application. Also, materials that are of similar viscosity will mix more easily in automated meter-mix-dispense (MMD) equipment than materials with widely different viscosity values.

Fillers are solid materials that are frequently added to enhance the properties of the organic material. Reinforcing fillers are often added to enhance properties such as strength, toughness, crack resistance, shrinkage during cure, and thermal expansion coefficient. Fillers can be particulate or platy minerals (e.g., silica, mica, clays) or fibrous materials (e.g., fiberglass, carbon fibers), depending on the requirements of the formulation. High aspect ratio or high surface area fillers can also affect the rheology of the uncured components. Some fillers may also serve additional functions, such as thermal (e.g., aluminum oxide, boron nitride) or electrical (e.g., silver powder or flake) conductivity. Depending on the application, the filler loading can be a small amount or a large percentage of the weight and volume of the total formulation.

Pigments are solid or liquid materials with an intense color used in small amounts to provide a color contrast between the resin and hardener in a 2K formulation so that it is possible to see visually whether the materials are adequately mixed. Pigments may also be used to provide color to a material so that it can be visualized on the substrate surface to ensure quality of dispensing. Some pigments, such as carbon black, graphite, and iron oxides, can provide secondary benefits to rheological or other properties.

Fire retardants are used to increase the flame resistance of formulations, typically assessed by the UL 94 flame test. These materials can be phosphate-rich organic molecules or hydrated minerals that will release water upon heating. The amount of fire retardant will depend on the type of material, the organic matrix, and the desired flame-resistance level.

Adhesion promoters are added directly to the formulations in relatively small amounts to improve adhesive strength to the desired substrates. These materials usually have a high affinity for the bonding surface and frequently also have a group on the molecule that is compatible or reactive with the organic matrix. Materials that contain adhesion promoters generally do not require a separate primer for the surface, which simplifies the manufacturing process.

Initiators, accelerators, catalysts, and inhibitors are all used, generally in small amounts, to regulate the rate of the chemical reaction in thermoset formulations. Initiators respond to heat or radiation (usually UV light) to generate the free radicals that initiate the radical chain reaction in materials using this mechanism. Only a small amount is needed because new radicals are generated as the reaction proceeds. Catalysts are small molecules that increase the rate of a chemical reaction but are not ultimately consumed in the reaction, so a small amount can be quite effective. Accelerators (or promoters) act to improve the reactivity of catalysts so that they are more effective, whereas inhibitors are used to decrease the effectiveness of the catalyst to slow down or moderate the reaction rate. Accelerators and inhibitors may be consumed as the reaction progresses.

5. ADHESIVES

5.1 Background and General Definitions

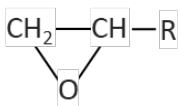
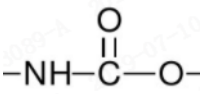
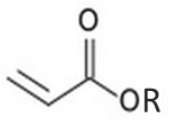
Structural adhesives are used in EV battery systems to bond battery components or encapsulate them to protect against environmental corrosion. Structural adhesives are applied on various areas in the battery system. In the case of prismatic hard case loaded battery packs, structural adhesives are used to bond the cells to the side panel and edge panel of the battery module and also used to bond the bottom of the modules or cells to the cooling panels. Additionally, elastic structural adhesives are used to bond the upper and lower housing of the battery pack to provide joining as well as sealing for the whole battery.

Structural adhesives generally have relatively high strength and modulus to bond rigid substrates. They provide reliable joining over the service years and offer improved stiffness, durability, and NVH (Noise, Vibration, and Harshness) compared to mechanical fasteners. In this section, detailed information on structural adhesives will be presented, including typical adhesive classifications, chemistry, and key material properties and characterization methods. Specific examples of battery systems applications containing structural adhesives can be found in Section 9. For an even deeper discussion of the chemistry and technology of structural adhesives, including UV-cured adhesives, the reader is directed to the references herein [3][4].

5.2 Structural Adhesives Classifications

Structural adhesives are typically classified based on their matrix as either thermosetting or thermoplastic. The majority of adhesives used in battery systems are thermosetting materials, though there exist a limited number of thermoplastic adhesives, also known as hot-melt adhesives. Table 4 summarizes the most common classes of adhesive chemistries, their defining reactive functional group, and corresponding features. The typical classes of adhesive chemistries are epoxy, polyurethane, and acrylate.

Table 4 - Typical characteristics of the most common kinds of adhesives

Matrix Chemistry Class	Associated Chemical Structure	Features
Epoxy		High strength Low elongation High-temperature resistance Chemical resistance Good adhesion to porous substrates
Polyurethane		Moderate elongation Moderate temperature resistance Good bonding performance on plastics
Acrylate		Fast curing speed Acid and alkali resistance Thermal stability (cold and heat) Good bonding performance on metal

5.3 Structural Adhesives Constituents

Table 5 provides a summary of the key constituents within structural adhesives. The resin constituent, also referred to as the matrix, strongly affects the mechanical and chemical material properties of the adhesive. Section 4 provides a detailed discussion on the chemistries commonly used as the matrix, including urethanes, acrylates, and epoxies. The manufacturing and end-use requirements for a given application will dictate the final selection of matrix material. The other key constituents for adhesives are the adhesion promoters used to enhance adhesive strength and the fillers used to enhance the cohesive strength of these materials. Adhesion promoters are selected based on the types of surfaces to bond and the nature of the cure chemistry used in the base polymer system. Filler particles vary in shape (e.g., spherical, rods, flake-like, spheroidal, tabular, etc.) and in size, ranging from nanometers to microns in length, depending on the specific needs of the application. Typical fillers include quartz and silica, which can provide significant modification to the mechanical properties due to the very high surface areas associated with these filler materials. These filler materials contribute mainly to modulus and tensile strength. For structural adhesives, higher modulus and tensile strength are essential; as a result, mainly polyurethane and acrylic chemistries are used as binders for structural adhesives.

Table 5 - Summary of key constituents in structural adhesives

Constituent	Role
Resin (e.g., isocyanate/hydroxyl function resins, acrylate monomer, epoxy/amine functional resins)	Controls cure trigger and baseline mechanical performance
Adhesion promoter	Enhances adhesive strength to substrate
Reinforcing fillers	Enhance modulus and tensile strength
Catalysts/Accelerators	Speed up the rate of reaction of the resin components
Pigments	Provide color, opacity, and fastness to light
Anti-corrosion additives	Improve corrosion resistance
Anti-sagging additives or fillers	Improve sag resistance
Fire retardants	Provide fire-resistance properties to reduce thermal runaway and catastrophic propagation

5.4 Evaluation Criteria

5.4.1 Physical and Mechanical Properties

Structural adhesives are expected to maintain mechanical integrity over the lifetime of mobility applications. For passenger vehicles, this could be more than 15 years, which stresses the importance of mechanical properties such as tensile strength, lap shear strength, T-Peel strength, and fracture toughness. These properties must also be well understood over a wide range of temperatures. Lap shear strength is usually in the range of about 5 to 20 MPa, with a similar range for the tensile strength of the adhesive. The elastic modulus is typically in the range of 30 to 2000 MPa, depending on the application area. Table 6 summarizes the most common mechanical properties and corresponding test methods.

Table 6 - Mechanical properties of adhesives and the corresponding characterization methods

Property (Units)	Definition	Test Method or Instrument Name	ASTM/ISO Reference
Tensile strength (MPa)	Maximum tensile stress before breaking adhesive specimen by pulling the adhesives in tensile mode	Tensile test/universal tensile testing	ASTM D638
Elastic modulus (MPa)	Modulus of the material within the linear or elastic region obtained during tensile or shear testing of the adhesive material	Tensile test/universal tensile testing	ASTM D3983
Shear strength (MPa)	Maximum shear stress that an adhesive joint can withstand in shear mode using a lap shear specimen	Lap shear test	ASTM D1002
Peel strength (N/m)	Maximum peel stress and energy that an adhesive joint can withstand in peel mode using a T-Peel specimen	T-Peel test	ASTM D1876
Impact strength (MPa)	Maximum stress and energy that an adhesive joint can absorb during dynamic impact loading using a drop tower test	Impact test/drop tower	ASTM D256
Fatigue strength (MPa)	Resistance of an adhesive to cyclic loading	Fatigue test	ASTM D3166

In addition to understanding the strength of a bond between an adhesive and a substrate, it is essential to understand the failure mode between the materials. The two most recognizable failure modes to consider are the Cohesive Failure (CF) mode and the Adhesive Failure (AF) mode. In CF mode, as shown in Figure 2 (left), the adhesive material fails within itself; that is, the bond to the substrate is not the weak link. In AF mode, as shown in Figure 2 (right), the failure occurs at the interface of the substrate and the adhesive.



Figure 2 - CF mode (left); AF mode (right)

Of these two basic failure modes, the CF mode is generally preferred as being more reliable than the AF mode. The failure within the homogeneous adhesive should be more consistent. Many other failure modes exist as can be viewed, for example, in ASTM D5573.

Additionally, for the battery application, the density of the structural adhesive should be as low as possible due to the energy density requirements of the entire battery pack. The typical density for adhesives is in the range of about 1.0 to 1.8 g/cm³. Some level of thermal conductivity is required for applications that need to conduct heat. The thermal conductivity level is usually in the range of 0.4 to 1.5 W/m·K, determined by the loading level of thermally conductive pigments within the structural adhesive. For adhesives that are in direct contact with cells, volume resistivity greater than 10¹² Ω·cm is also required.

5.4.2 Rheology and Cure Kinetics

Rheology of structural adhesives substantially affects their usage and shape stability before curing. The requirements for the rheology of structural adhesives vary with different applications. For adhesives applied in a vertical position, good sag resistance is needed; however, some applications need the adhesives to be self-leveling with good surface wetting and filling properties. Viscosity and yield stress are two important properties that indicate the dispensing flow rate and sag resistance, respectively, and these properties can be typically characterized using a rotational rheometer at different shear rates and temperatures.