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

RATIONALE

This Information Report introduces the basic concepts, properties, and dispensing of adhesives, sealants, and heat transfer materials (HTMs) and the roles they serve in applications within battery systems.

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1. SCOPE

This SAE Information Report introduces key concepts and properties of adhesives, sealants, and 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 (inside USA and Canada) or +1 724-776-4970 (outside USA), 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 Other Publications

- [1] "Contemporary Polymer Chemistry," 2nd Edition, Allcock, H.R. and Lampe, F.W., Prentice Hall: 1990.
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- [3] "Structural Adhesives: Chemistry and Technology," Hartshorn, S.R., ed., Springer US: 1986.
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- [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] “Extruded and ribbed thermal interface for use with a battery cooling system,” Tennessen, P.T., Weintraub, J.C., and Hermann, W.A., 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 heat transfer materials (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 heat transfer materials (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 crosslink and remain essentially unchanged after repeated processing. In contrast, thermosets are generally liquids or pastes at ambient temperature that, due to mixing of two components and/or exposure to elevated temperature, undergo a chemical reaction, commonly termed cure, to give a solid material that cannot be directly re-processed. 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 result of their crosslinked network.

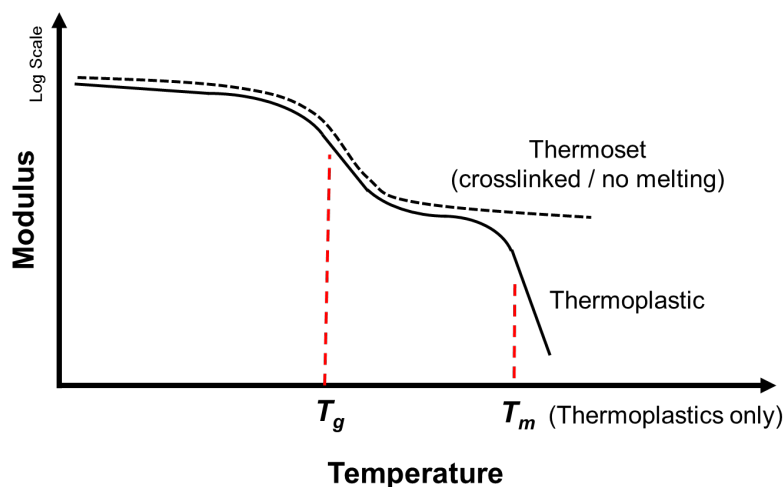


Figure 1 - Conceptual DMA curve (modulus - log scale versus temperature) showing the glass transition, T_g (thermosets, dashed line, and thermoplastics, solid line) and the melt behavior of amorphous thermoplastics

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 re-use 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 crosslinked 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 crosslinking 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 have 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, and epoxy materials

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

* 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	$\left(\begin{array}{c} \text{CH}_3 \\ \\ -\text{Si}-\text{O}- \\ \\ \text{CH}_3 \end{array} \right)_n$
Polyurethane	$-\text{NH}-\overset{\text{O}}{\underset{\text{ }}{\text{C}}}-\text{O}-$
Acrylate	$\begin{array}{c} \text{O} \\ \\ \text{CH}_2=\text{CH}-\text{C}-\text{OR} \end{array}$
Epoxy	$\begin{array}{c} \text{CH}_2-\text{CH}-\text{R} \\ \quad \quad \\ \text{O} \end{array}$

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 or 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 crosslinks 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 type 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.

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

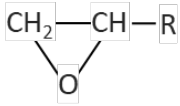
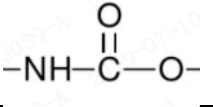
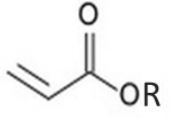
Structural adhesives are used in EV battery systems to bond battery components or encapsulate them to protect against environmental corrosion. Structural adhesives are applied on various areas in the battery system. In the case of prismatic hard case loaded battery packs, structural adhesives are used 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	Enhances 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	Provides 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 D638-14
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 D3983-98
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 D3330
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

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.

In general, structural adhesives have an optimum cure temperature, which can be characterized by differential scanning calorimetry (DSC) using isothermal or temperature ramp experiments. Table 7 shows a summary of the associated test methods for evaluating adhesives.

Table 7 - Rheological and cure properties of adhesives and the corresponding characterization test methods

Property (Units)	Definition	Test Method or Instrument Name	ASTM/ISO Reference
Viscosity (mPa·s)	Resistance to flow	Shear stress versus shear rate at different temperatures using a rheometer	ASTM D2556
Yield stress (MPa)	Maximum stress before the adhesive starts to flow	Shear stress versus shear rate at different temperatures using a rheometer	ASTM D7836-13
Dispensability	Ability of an adhesive to be dispensed through a dispensing system	Custom	N/A
Sag resistance	Resistance of an adhesive to keep its initial shape under gravitational force in vertical direction	Standard test method for slump of sealants, or Custom tests	ASTM D2202
Kinetic parameters of cure reaction	Parameters that determine kinetics of cure reaction, e.g., activation heat or reaction, reaction rate constant energy, reaction order, etc.	Differential scanning calorimetry (DSC) test	ASTM E2041-13

5.4.3 Environmental Resistance

Structural adhesives applied in EV battery systems are exposed to various environmental conditions. The variation of static and dynamic loads, temperature or weather cycling can significantly influence the bonded joints. It is essential to evaluate the mechanical properties under different environmental conditions, such as high humidity, high temperature, or corrosive ambient. Additionally, aging is another factor that needs to be considered in characterizing adhesives' environmental resistance. Table 8 represents different test methods that are used to characterize adhesives' properties under different environmental conditions.

Table 8 - Adhesive properties under environmental conditions

Property	Definition	ASTM/ISO Reference
Stress durability	Durability of adhesive joints stressed in different modes and exposed to moisture and/or other environmental conditions	ASTM D2918-99 ASTM D2919-01
Corrosion resistance	Expose an adhesive to corrosive environments and evaluate performance after exposure	N/A
Humidity resistance	Change in adhesive properties due to exposure to humidity	ASTM D 2247
Accelerated aging conditions	Aging conditions changed based on the different materials. Aging often conducted at higher temperature to accelerate the rate of property degradation.	ISO 9142

5.5 Application Technology

Structural adhesives can generally be dispensed manually or robotically. When applying manually, proper pneumatic or battery-operated dispense guns are utilized to dispense the adhesive from the package, typically in the form of cartridge. Spraying methods are sometimes utilized for low-viscosity and self-leveling adhesives. For automated application, a pump is generally used together with a proper metering system and robotic arms for dispensing the adhesive with defined volume and position on the batteries. A more in-depth overview of dispensing of adhesives can be found in Section 8.

5.6 Health and Ecological Environment Considerations

Adhesive solutions for battery systems must also be considered in conjunction with health, safety, and environmental regulations and corporate requirements. Examples of topics covered by these regulations and requirements include, but are not limited to:

- Solid content, ash content.
- Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) or other similar regulations compliance.
- Odor, fogging, total volatile organic compounds (VOC), and specific compound emission limits.

Accommodation for re-working of components may also be considered in designing battery applications using adhesives. As the structural adhesives are used to fix cells and modules, it is difficult to disassemble the cells due to the strong bonding force. Specifically, if an individual cell failure occurs, the other cells might be impossible to be re-assembled, and the whole module will be scrapped. In addition, temporary rework is unavoidable during the assembly process. Therefore, the structural adhesives should be removable and easy to clean using some chemical or physical methods, considering that repairability is an important design principle for automobile parts.

6. SEALANTS

6.1 Background

Sealant materials, alternately termed sealers and sealing materials, are designed to form a barrier through a combination of both the properties of the sealant and its adhesion to the substrate. Sealant materials must prevent both ingress and egress of a variety of items including air, gas, noise, dust, fire, smoke, or liquids. Sealant materials can also have the secondary functions of filling and covering gaps in the final component as shown in Figure 2.



Figure 2A

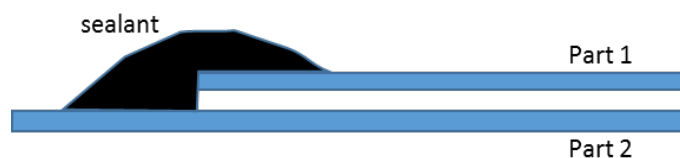


Figure 2B

Figure 2 - (A) gap filling and (B) covering functions for sealant materials

Unlike adhesives, structural bonding is not required of sealant materials. Typically, sealants are employed in combination with other structural components such as screws, welds, or structural adhesives that are designed to maintain rigid assembly. Occasionally, a sealant with sufficient adhesion strength may be considered to keep a battery pack permanently closed and sealed, in which case a sealant may also function as an adhesive material.

In addition to filling and covering gaps, sealant materials can also deliver secondary performance properties such as increased stiffness and/or impact resistance (see structural adhesives) and thermal (see HTM) or electrical conductivity. The need for these properties highly depends on the battery pack design and associated process design. For a supplemental information on sealant chemistry and technologies, the reader is directed to the reference herein [5].