Green chemistries for use as electrical insulation

Brian Chambers
Star Technology
Waterloo, Indiana
bchambers@star-technology.com

Nancy Frost, Ph.D
Frosty's Zap Lab, LLC
Menands, NY
drnancyfrost@gmail.com

***Abstract*— In August of 2021, UN Secretary-General António Guterres said that a recent report published by the Intergovernmental Panel on Climate Change (IPCC) is a "code red for humanity." Adding that "This report must sound a death knell for coal and fossil fuels, before they destroy our planet… Countries should also end all new fossil fuel exploration and production, and shift fossil fuel subsidies into renewable energy." Of course, Secretary Guterres wasn't too concerned about the use of fossil fuels to produce epoxy or polyurethane resins for dielectric compounds, clearly, he was speaking about the burning of fossil fuels for energy production and transportation. However, those of us in the industry will recognize that the search for materials from renewable resources is fast becoming an industry standard. Scientists across the globe are exploring alternatives to hydrocarbon feedstocks for producing polymers, fibers and other critical raw materials. Here we will examine the status of that exploration to determine feasibility and take a look at some new materials and compare their performance to existing systems. Then we will revisit an existing chemistry, in production for nearly three-quarters of a century; manufactured from the most abundant substance on the planet and already nearly free from fossil fuels - silicones. Finally, to complete the cycle, we will take some of these "green chemistries" and investigate where they may apply in the applications of today's climate.**

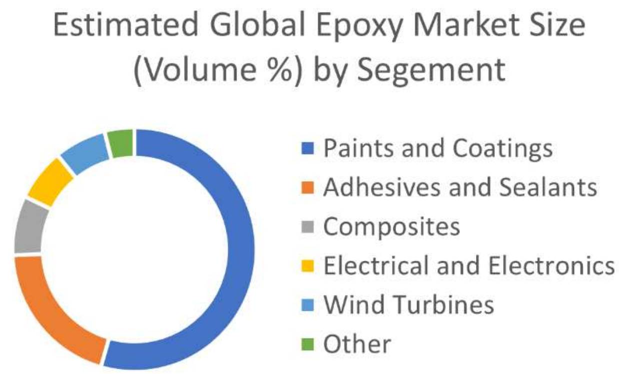
Keywords*— *bio-based, biorenewable, epoxy, potting, insulating

I. INTRODUCTION

As the world transitions away from fossil fuels the search for alternative materials is rapidly intensifying. In many sectors, scientists are investigating different pathways to synthesize and produce polymers, resins, fibers and other critical materials from alternative feedstocks. Even if the world does not transition away from fossil fuels today, oil supplies are finite and will eventually run out ultimately forcing us to find replacements. Nearly everybody using materials derived from fossil fuels is exploring different techniques to reduce consumption and thereby lower their carbon footprint and ease their dependence. This is not an easy venture; clearly, the search is happening at the right moment in history.

This concept of a carbon footprint, nearly unheard of a mere 20 years ago is now ubiquitous in society. Companies producing everything from automobiles to zinc sheet promote some level of environmental concern. "Green chemistries" are exploding in nearly every market; "exploding" might be a slight exaggeration, but certainly the drive for companies to lower their carbon footprint and move to more earth friendly processes is significant.

The numbers vary wildly, but in 2020 the global combined total of epoxy and polyurethane resins market was estimated between USD 62.55 and 82.29 billion. [1,2,3,4] Polyurethane percentage exceeds epoxy percentage by nearly 10:1 margin. Of course, the fraction of these materials that are used in electrical insulation applications is exceptionally small. Paint and coatings dominate the epoxy market whereas furniture and construction lead the polyurethane market. Because we use such small volumes, those of us who formulate encapsulants and potting compounds will not direct the development of new chemistries; however, we will reap the benefits of any innovation.



Beyond the need to transition away from fossil fuels, a significant portion of the new developments are in response to a growing awareness of consumers who are asking for safer, more environmentally friendly materials. For example, bisphenol A, more recognizable by the acronym BPA, is found in many commercial products including water bottles, storage containers and even some baby pacifiers; unfortunately, studies indicate that BPA mimics estrogen in the body and has negative impacts on our endocrine systems. While not banned outright, consumer demand for BPA free products is intensifying. In response to this consumer lobbying there are now biobased and biodegradable alternatives to BPA.

The US Secretary of Agriculture defines bio-based products as commercial or industrial materials that are composed in whole, or in significant part, of biological products or renewable agricultural or forestry materials. In the literature, terms used synonymously with bio-based include renewable, plant-based, bio-derived, bio-renewable, sustainable among others. Often products are not derived 100% from bio-based materials, but only a fraction of the total is bio-based with the remainder still coming from petroleum. Several standardized tests, such as

ASTM D6866,[5] have been developed to quantify the bio-content of a product or material.

“Bio-refining” is the process whereby renewable agricultural feedstock, sometimes referred to as the biomass, is converted into useful fractions, chemicals and polymers. The technologies used vary depending upon the composition of the feedstock and the intended results; they encompass physical, chemical and even microorganism conversion. Often, the first step in this conversion process starts with vegetable/tree oils or sugars, to produce chemical building blocks, which are then further converted to secondary chemicals or families of derivatives. Of particular interest is using sustainable chemistries to produce monomers, which may be polymerized for application into plastics and elastomers for coatings, sealants, adhesives and encapsulants. It is these bio-renewable materials that form the basis of our current investigation.

II. BACKGROUND INFORMATION

Perhaps a brief review of the current fossil fuel derived chemistries is an appropriate point to launch our discussion. Some of the original patents around both epoxy and polyurethane chemistry date back to the 1930’s. The first commercial applications are found in the early 1950’s. After over seven decades, the variety of products and applications is extraordinary, and the list continues to grow. While there are numerous variations, the base chemistries remain fairly consistent.

A. Epoxy Systems

Figure 1 shows the reaction scheme for a typical amine cured epoxy. Undoubtedly one of the most popular types of all epoxies, these systems are generally packaged and sold as two components that are mixed just prior to application. The “B” side also known as the “hardener”, is the epoxy curing agent. In this scenario, the amine in the curing agent is responsible for reacting with the epoxy groups contained in the epoxy resin “A” side. Reaction of curing agents with epoxy resins results in hard, thermoset materials. The epoxy resin is the result of the reaction of bisphenol A with epichlorohydrin, both of which are ultimately derived from fossil fuels. Bisphenol A is the reaction product of phenol with acetone. First extracted from coal tar, today phenol is produced on a large scale (about 7 billion kg/year[6]) from petroleum-derived feedstocks.

There are literally hundreds of different amines that may be employed as epoxy curing agents most of which are again derived from petroleum feedstocks. The available types of amine-based epoxy curing agents include polyamides, amidoamines, aliphatic amines, cycloaliphatic amines, and phenalkamines. To fully cross-link the system, curing agents must have more than three active hydrogen atoms and two amino groups on each molecule. Referring to Figure 1 it is noted that the epoxy and the amine-hydrogens react in a 1:1 ratio. As a general rule, use of a 1:1 stoichiometric ratio (SR) of amine hydrogen to epoxide groups will, when fully reacted, ensure maximum stability of the product. All of the mixes made throughout this study were reacted at slightly over 1:1 stoichiometric ratio. While this is the base chemistry, it is clearly an oversimplification as commercial products will often contain many different additives and fillers that will influence the ultimate physical properties.

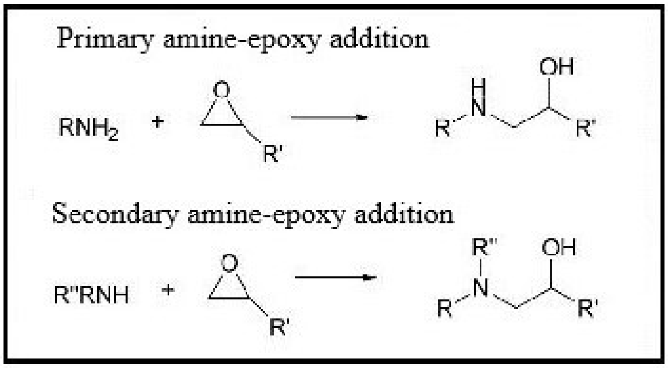


Figure 1. Epoxy and amine reaction scheme

A commercially available, amine-cured epoxy based on traditional diglycidyl ether of bisphenol A (DGEBA) derived from fossil fuels, serves as the commercial standard for several applications and represents our control for base comparison of bio-based alternatives. Physical properties are outlined in Tables 1 and 2 presented later in this document.

Alicyclic anhydrides are an alternate cure mechanism that provide excellent electrical properties for high voltage systems. While the base resins remain essentially constant the curing agent portion is an anhydride, or a blend of anhydrides. The reaction scheme is shown in Figure 2. Here too, the raw materials are predominately derived from petroleum feed stocks. Anhydrides are commonly employed in more challenging applications including fiber reinforced composites for high performance aerospace and military applications and physically demanding applications like filament wound bearings. A commercially available anhydride cured epoxy based on traditional bisphenol A and serves as the anhydride control in our study. Physical properties and general characteristics are presented in Table 3.

Anhydride-cured chemistries are available as both single-component and two-component systems. Care must be observed to eliminate moisture during the manufacturing process as most anhydrides are moisture sensitive and will react prematurely. Note the resulting ester linkages in Figure 2. These ester linkages in the final product present the greatest drawback of anhydride cured epoxies as they are susceptible to hydrolysis in conditions of high humidity or water immersion. If the epoxy is exposed to high temperature and water the matrix can hydrolyze and revert to a liquid in as little as 24-48 hours. Final physical properties of anhydride cured systems are highly influenced by the cure cycle. Generally, low initial temperatures followed by a high-temperature post cure favors increased cross-linking, which results in increased mechanical strength and improved chemical resistance.

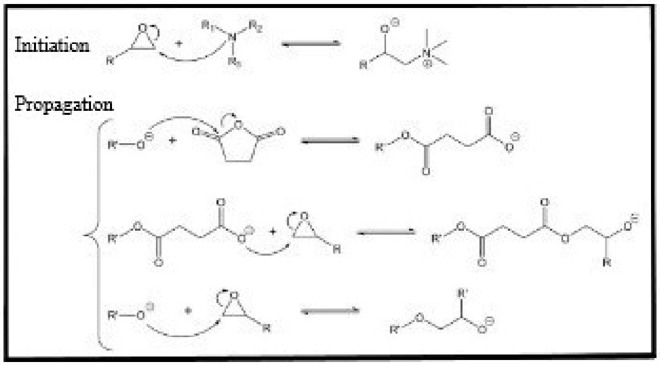


Figure 2. Epoxy and anhydride reaction scheme

With no mixing required, single-component systems simplify the application process; however, the high-temperature required for curing may present a problem for some heat sensitive substrates. Among a variety of applications, these materials are often found in vacuum, pressure impregnating (VPI) tanks.

In both amine and anhydride cured epoxies, as well as single-component latent cure epoxies, reactive diluents and modifiers are often employed to reduce viscosity, improve flexibility and lengthen the pot-life. These ingredients may be present in the formulation at concentrations up to 50% and may be single compounds, or blends of two or more depending upon the desired results. As we will discuss later, many of these constituents are already bio-based; however, some of the most prevalent are still derived from petroleum.

B. Polyurethanes

At its most elementary a polyurethane is the reaction product of an isocyanate with either a polyether or a polyester polymeric polyol. The choice of which isocyanate(s) and which polyol(s) determines the physical properties of the system. The choices are nearly limitless. While even in these traditional materials there are some polyols that are produced from natural resources, such as castor oil, the majority of materials are still from petroleum-derived feedstocks. As shown in Figure 3, commercial isocyanates are generally subdivided into two groups – aliphatic and aromatic. Most isocyanates are manufactured using phosgenation (i.e., treating an amine with phosgene). Because of the hazards associated with handling and storage of explosive and toxic compounds, a long and difficult search continues for an effective alternative to phosgene-based processing.

As mentioned, there are some bio-based polyols, which we will discuss later; however, most commercially available polyurethanes are based on either polyether or polyester polyols. Polyether polyols are most commonly prepared from either propylene oxide and/or ethylene oxide in the presence of a catalyst. The oxides are in turn prepared from propylene and ethylene, which are two of the most important products used in the petrochemical industry. Polyester polyols are made by the polycondensation reaction of multifunctional carboxylic acids, or anhydrides and polyhydroxyl compounds (diols and triols). Common polyester polyols such as polycaprolactone, polyglycolide, and polylactide are often found in biodegradable polyurethanes, although the monomers used to produce these polymers are currently still mostly fossil fuel based.

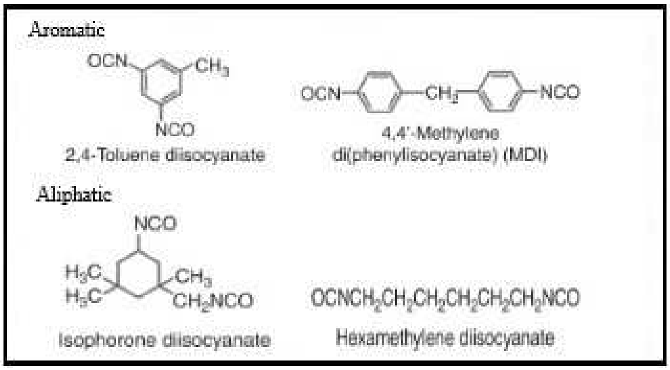


Figure 3. Select isocyanates (Aromatic and Aliphatic)

In nearly every formulation, regardless of the base chemistry, there are a number of minor ingredients that will greatly influence the nature of the product, the ultimate physical properties and appearance of the final application. There are countless variations of these additives, most of which are surface active agents, also known as surfactants. Dispersants as the name implies, aid in dispersing fillers and pigments. Flow and leveling agents provide a smooth defect free surface. Air release, substrate wetting, surface slip are just a few of the many characteristics enhanced by additives.

C. Physical Properties and Test Methods

Several important physical properties give a strong indication of performance in an application. It is essential for any new raw material innovation to meet well established guidelines to ensure success. Handling characteristics, mechanical properties, electrical properties and thermal behavior will all contribute to a product's effectiveness in achieving performance goals.

III. RESULTS AND DISCUSSION

From the above discussion it is evident that there are a number of different opportunities to reduce fossil fuel dependencies and improve the overall environmental impact by moving to bio-based production. The difficulty lies in finding techniques and methods to replace petroleum feedstocks with bio-renewable materials without compromising the ultimate physical properties of the final product. Fortunately, chemists are like wizards, capable of creating almost miraculous transformations. In some instances, the knowledge and technology to complete the transition may already exist. With only a small capital investment the lower cost of a certain biomass may be exploited, and the benefits of bio-renewable fully realized. As companies continue to investigate options, the frequency of this win-win scenario continues to rise.

A. Bio-based Epoxies

Through the innovative efforts of a bio-based chemical company in Thailand, it is now possible to produce epichlorohydrin from natural vegetable glycerol. According to the company bio-based epichlorohydrin results in a 61% reduction in CO_2 when compared to oil-based production (34% due to carbon capture from plants and 27% due to lower greenhouse gas emissions). Simply using this epichlorohydrin, which is 100% bio-based in conjunction with standard bisphenol A, which is 0% bio-based yields an epoxy resin with 28% bio-based content. A global chemical supplier provides a commercialized bio-based product believed to be based on this chemistry. As evidenced by the data presented in Table 1, these resins are nearly an exact drop-in replacement for fossil fuel derived epoxies.

Table 1. Amine Cured Epoxies With 28% Bio-Based Bisphenol A Resin

Test Method	Amine Control	Bio-Based Alternative
Gel Time	273 mins @ 100 g	188 mins @ 100 g
Viscosity	8040 cps @ 10 rpm	12,400 cps @ 10 rpm
Hardness (Shore D)	77D	76D
Tg	102°C	105°C
Flexural Strength	11,640 psi	10,460 psi
Compressive Strength	10,980 psi	9460 psi
Dielectric Strength	285 V/mil	309 V/mil
Dielectric Constant	2.38 @ 100kHz	2.35 @ 100 kHz
Dissipation Factor	0.0166 @ 100 kHz	0.0160 @ 100 kHz

28% Bio-based with no reduction in physical properties is an attractive starting point, but the ultimate target is 100% bio-based. Is it even possible to achieve such a lofty goal? Research to date indicates that in both epoxy and polyurethane systems achieving 100% bio-based is not possible. Material properties fall short and bio-based raw materials must be supplemented by blending with traditional fossil fuel derived products. Additionally, the selection of available raw materials is still limited. Reducing the formulator's palette of ingredients is like forcing an artist to paint with only one color – you might get some interesting pictures, but the designs will not be as spectacular.

While it may not be possible to achieve 100% bio-based in every application, any amount of renewable carbon in a product helps reduce our footprint. The selection of raw materials and the amount of bio-based content will vary significantly depending upon the chemistry. Our efforts focus predominately on alternative epoxy chemistries, but there are some experiments with polyurethane bio-based alternatives. The data presented evaluates several different bio-based materials blended at varying ratios with traditional fossil fuel-based products. As the "B" component in each mix remains constant and our focus is strictly on the resin components, the percentage of bio-renewable content listed is for the resin, or "A" side only. There are several biobased alternatives for curing agents.

A by-product of the paper pulping industry, crude tall oil (CTO) is a valuable biomass that is rich in carbon resources for bio-refining. More readily available in pine trees and other conifers rather than deciduous trees, rosin is an important component of CTO. As with many bio-based resources, rosin consists of a blend of various constituents – principally abietic acid and pimaric acid. Without further modification, rosin is a brittle, glassy solid that may be used as an ingredient in printing inks, varnishes, adhesives and even the lead-tin solder commonly used in electronics has 1 to 2% rosin by weight as a flux core. Another derivative from the bio-refining of CTO is a complex mixture of tall oil fatty acids and rosin isomers identified as distilled tall oil (DTO).

At a leading global manufacturer of specialty chemicals and high-performance carbon materials, chemists modify DTO and rosin to create a portfolio of commercialized epoxy raw materials. Ranging in bio-renewable content from 44% to 99% these materials form the basis of our second round of testing as outlined in Table 2. It is important to note that the chemistries of these materials are significantly different. While convenient, choosing to analyze and represent the data based solely on the bio-renewable content may provide a slightly skewed picture of overall performance. The model compounds presented are stripped of all but the most essential ingredients to better capture any effect of the bio-based content. With proper formulation techniques deficiencies within any one system may be compensated.

Other important bio-renewable resources are carbohydrates and sugars derived not from trees, but from plants such as corn, soybeans, rice, grass, fruits and other vegetables. Sorbitol is a sugar alcohol naturally produced in various plants as a result of photosynthesis. Sorbitol is found naturally in berries like blackberries, raspberries and strawberries, and other fruits such as apples, apricots, avocados, cherries, peaches and plums. However, most sorbitol is currently produced from potato starch. Each molecule of Sorbitol contains 6 hydroxyls ready for further modification. Epoxidation with epichlorohydrin yields a tetrafunctional glycidyl ether that may act as a potential replacement for DGEBA. Another leading global manufacturer of specialty chemicals provides a product based on sorbitol with 18% bio-based content. It is assumed that the material is only 18% bio-based because the epichlorohydrin used in the modification was not the bio-based epichlorohydrin mentioned earlier in this paper. Had the manufacture chosen to use bio-based epichlorohydrin the amount of bio-renewable content could approach 100%.

Table 2. Comparison of Physical Properties of Amide-Cured Epoxy at Varying Ratios of Biobased Content

Property	Amine Control	87% Bio-Base	65% Bio-Base	22% Bio-Base	18% Bio-Base
Source	Fossil Fuel	Rosin (CTO)	Rosin / DTO Blend	DTO Blend	Sorbitol
Gel Time	273 mins @ 100 g	162 mins @ 100 g	169 mins @ 100 g	183 mins @ 100 g	43 mins @ 100 g
Viscosity	8040 cps @ 10 rpm	38,800 cps @ 10 rpm	40,000 cps @ 10 rpm	19,600 cps @ 10 rpm	14,800 cps @ 10 rpm
Hardness	77D	75D	65D	75D	75D
Tg	102°C	80°C	55°C	74°C	90°C
Flexural Strength	11,640 psi	2,880 psi	2,105 psi	8,450 psi	8,680 psi
Compressive Strength	10,980 psi	380 psi	12,325 psi	8375 psi	12,140 psi
Dielectric Constant	2.38 @ 100kHz	2.78 @ 100kHz	2.75 @ 100kHz	2.54 @ 100kHz	3.29 @ 100 kHz
Dissipation Factor	0.0166 @ 100 kHz	0.0136 @ 100 kHz	0.0188 @ 100 kHz	0.0133 @ 100 kHz	0.0289 @ 100 kHz
Dielectric Strength	285 V/mil	274 V/mil	279 V/mil	292 V/mil	

Note: All systems cured with Ancamide 375A from Evonik at 1:1.05 stoichiometric ratio. Post cure overnight @ 100C

Table 3. Comparison of Physical Properties of Anhydride-Cured Epoxy at Varying Ratios of Bio-Based Content

Property	Anhydride Control	87% Bio-Based	28% Bio-Based
Source	Fossil Fuel	Rosin (CTO)	Bio-based epichlorohydrin
Viscosity (Brookfield)	1050 cps @ 10 rpm	4,470 cps @ 10 rpm	1200 cps @ 10 rpm
Hardness	80D	79D	80D
Tg	146°C	95°C	146°C
Flexural Strength	12,690 psi	655 psi	13,105 psi
Compressive Strength	84,260 psi	33,550 psi	13,420 psi
Dielectric Strength	293 V/mil	291 V/mil	276 V/mil
Dielectric Constant	2.54 @ 100kHz	2.62 @ 100kHz	2.72 @ 100 kHz
Dissipation Factor	0.0598 @ 100 kHz	0.0142 @ 100 kHz	0.0142 @ 100 kHz

Note: All systems cured with Lindride 32 from Lindau Chemicals, Inc. plus catalyst

B. Bio-based Polyurethanes

While there are currently no acceptable bio-renewable alternatives for any of the common isocyanates used to produce polyurethane, there are still many options for bio-based polyols that may substitute for traditional polyether and polyester polyols. Some of these materials are naturally occurring and require little to no modification to perform as polyurethane feedstock, others are based on naturally derived materials and must be further modified to add or enhance hydroxyl functionality.

Ricinus communis, commonly referred to as the African Wonder Tree, the Castor Bean Plant, the Castor Oil Tree is native to tropical east Africa but has naturalized in tropical and subtropical areas around the world. Castor oil is extracted from the seeds of Ricinus communis. A mixture of several ingredients, the composition of castor oil is well documented to contain approximately 90% ricinoleic acid triglyceride [7,8]. Ricinoleic acid is a unique fatty acid ester with hydroxy functional group in its structure and castor oil derivatives have been used to make bio-compatible polyurethane for years.

A leading oleochemical supplier provides unique polyol technology based on naturally derived azelaic acid (C9 & C36 diacids) and other fatty acids. Based on well-established azelaic or dimer acid feedstocks offering high bio-based content from 69-99%, depending on grade. Performance data for both the castor oil and the dimer acid (Dimerate) polyols is shown in Table 4. compared to a traditional 1000 m.w. polyether diol. These model systems are cured using a polymeric MDI from BASF (Luprinate M10).

Table 4. Comparison of Properties for Polyurethanes from Bio-Based Polyols

Property	Polyether	Castor Oil	Dimerate
Hardness	55A	80A	65A
Water Absorption	3.3 % 7 Days @ RT	2.2% 7 Days @ RT	2.1% 7 Days @ RT
Dielectric Strength	225 V/mil	293 V/mil	271 V/mil
Dielectric Constant	6.35 @ 100 kHz	NA	3.22 @100 kHz
Dissipation Factor	0.1381 @ 100 kHz	NA	0.1590 @ 100 kHz

IV. SILICONES

Often confused with silicon, the 14th element on the periodic table, silicone (with an "e") is an elastomeric material derived from silica. Composed of the two most abundant elements in the Earth's crust, silicon and oxygen, silica is commonly found in nature as sand. Though technically not a bio-renewable resource, the sheer volume of available silica coupled with the ease of extraction certainly puts less stress on the environment than fossil-fuel derived hydrocarbons. Described as an inorganic/organic molecular hybrid, the polymeric backbone of silicone contains the inorganic portion (Si-O), and the pendant functionality is generally hydrocarbon as shown in Figure 4.

This dual nature of silicones provides the unique properties associated with the chemistry. Unique properties should not imply better, or superior, as each chemistry presented here has both advantages and disadvantages. A certain chemistry may be better suited for a particular application and would therefore be the superior choice for a given set of conditions. Silicones, for instance, are non-polar, extremely UV resistant and exceptionally hydrophobic making them the better choice for applications that are under constant water submersion or exposed to the elements. Silicone rubber can be immersed in water for prolonged periods with absorption of less than 1% and virtually no effect on mechanical or electrical properties. The insulating properties of a silicone are stable over a wide temperature range and across a wide frequency spectrum. Even when fully immersed under water there is almost no decline in performance.

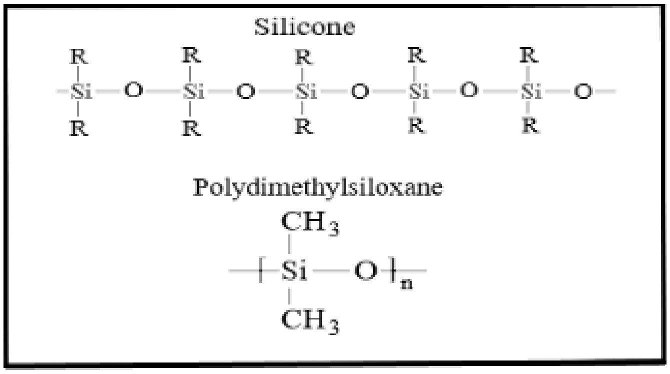


Figure 4. Basic Silicone Structure

Because the siloxane bonds (-O-Si-O-) of the silicone backbone are highly stable and relatively strong compared to carbon-carbon bonds of traditional hydrocarbon chemistries (433 kJ/mol versus 355 kJ/mol), silicone rubbers have higher heat resistance and better chemical stability than most epoxy and polyurethane compounds. Intermolecular forces are extremely low resulting in high elongation, and superior low temperature flexibility. When formulated properly the Tg of a good silicone rubber can approach or exceed -70ºC, which makes them ideally suited for aerospace applications.

There are four main cure chemistries in silicone applications. Single-component, moisture curing silicones like the tubes of caulking compound at the local hardware store, are by far the highest volume materials. Known for their ease of application, good adhesion and excellent weathering resistance these compounds are used extensively in construction applications. More prevalent in electrical insulating, potting and encapsulating two-component silicones both condensation cure and addition cure are excellent dielectric compounds. Unlike epoxy and polyurethane products, when mixed the reaction proceeds with virtually no exotherm, thus the gel time is independent of the mass or volume mixed. Heat cure rubbers (HCR) find little functionality in field applied materials. Used extensively in injection molding, HCR silicone insulators and arrestors are prevalent in high-voltage power transmission and distribution due to their excellent hydrophobicity, outstanding weather resistance and superior electrical properties.

Silicone rubbers also have outstanding electrical performance at elevated temperatures. Figure 5 shows the dissipation factor (DF) versus temperature for a candidate, addition-cure silicone rubber. Note the stable, low dissipation factor across a wide temperature range. Silicone rubbers also have good dielectric strength as shown in Figure 6.

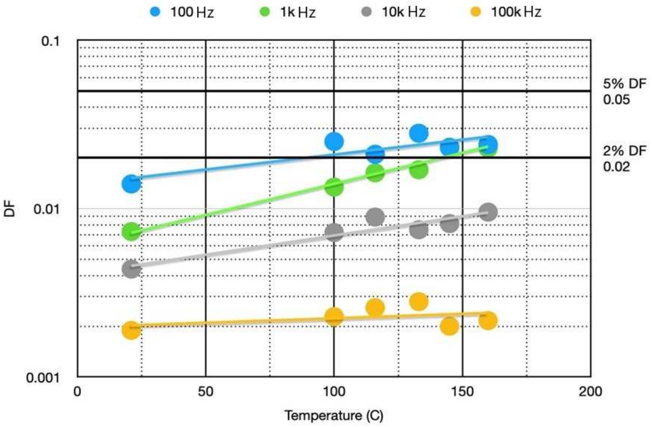


Figure 5. Silicone rubber DF versus Temperature – Decades

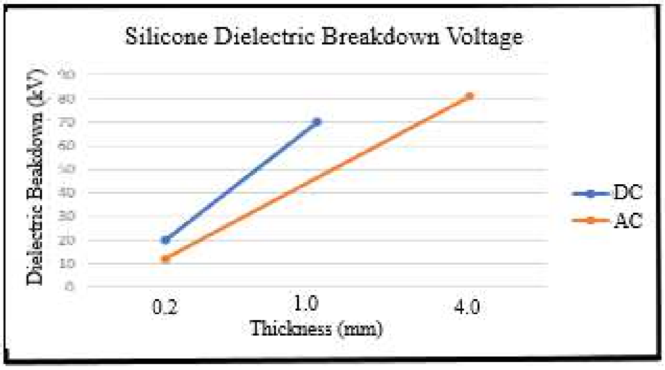


Figure 6. Dielectric breakdown voltage of typical silicone rubber (Shin Etsu Silicones)

V. CONCLUSIONS

Many times, products isolated from bio-renewable sources are not pure compounds. Often, they will contain isomers of a single compound, or several derivatives from a family of chemicals. More importantly, there are frequently impurities that cannot be practically removed. Water can be particularly devastating. Especially to moisture sensitive systems such as polyurethanes. When water reacts with an isocyanate, it generates CO_2 causing gassing. The castor oil polyols used in this study had high water content and while there are methods to dry the system those techniques are beyond the scope of this study. Samples prepared for testing some electrical properties had so many bubbles that it was not possible to test.

While there are some differences in the data, none of the epoxy alternatives exhibit any glaring deficiencies, or performance gaps that would preclude their use in potting or encapsulating applications. While the glass transition temperature (T_g) does not follow any particular trend, it is noted that the T_g for all of the materials that contain bio-based content with the exception of the bio-based epichlorohydrin material are 10-50ºC lower than traditional Bis A resin. This may limit their functionality in high temperature applications. Surprisingly, the viscosity of every biobased material is higher than the original bisphenol A derived from fossil fuels. Generally, starting with a resin that has lower viscosity makes formulating a little easier; however, higher viscosity alone should not disqualify any material as proper formulating techniques may be able to compensate. Electrical properties are comparable across all materials.

While it may not yet be possible to provide potting and encapsulating materials with 100% bio-renewable content the trend is certainly moving in the right direction. As the world slowly transitions away from fossil fuels, the push within the chemical industry is accelerating. Still, there are plenty opportunities for continued expansion and there is much work ahead and many more options to explore.

VI. ACKNOWLEDGEMENTS

The authors wish to acknowledge and express their gratitude to Joe Zimmerman and the entire team at Star Technology for their contributions and their support Melissa Eshbach, Casey Zimmerman, Ron Kumpfmiller, Genevieve DiPaolo. Thanks also to these companies that graciously donated samples and consultation Atul, Boehle Chemicals, Inc., Campbell & Company, Emery Oleochemicals, Ingevity, Huntsman Advanced Materials.

REFERENCES

[1] Epoxy Resin Market Size, Share & Trends Analysis Report By Application (Paints & Coatings, Construction), By Region (APAC, North America, Europe), And Segment Forecasts, 2021 - 2028

[2] "Polyurethane Market, 2021-2028." Polyurethane Market Size, Share & COVID-19 Impact Analysis, By Product Type (Rigid Foam, Flexible Foam, Molded Foam, Elastomers, Adhesives & Sealants, Coatings, and Others), By Application (Furniture, Construction, Electronics, Automotive & Transportation, Packaging, Footwear, and Others), and Regional Forecast, 2021-2028.

[3] Polyurethane Market Size, Share & Trends Analysis Report By Product (Flexible Foam, Rigid Foam), By End Use (Construction, Electronics & Appliances), By Region (APAC, North America), And Segment Forecasts, 2021 - 2028

[4] Epoxy Resin Market Share, Size, Trends, Industry Analysis Report By Formulation Type (DGBEA, DGBEF, Novolac, Aliphatic, Glycidylamine, Others); By Application (Paints & Coatings, Adhesives, Composites, Electrical & Electronics, Wind Turbines, Others); By Region, Segments & Forecast, 2021 - 2029

[5] ASTM D6886 "Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis" ASTM International, West Conshohocken, PA, 2018 DOI: 10.1520/D6866-16

[6] Weber, Manfred; Weber, Markus; Kleine-Boymann, Michael (2004). "Phenol". Ullmann's Encyclopedia of Industrial Chemistry. Weinheim: Wiley-VCH

[7] Valero MF, Pulido JE, Ramírez Á, Cheng Z. Polyurethanes sintetized of polyols obtained from castor oil modified by transesterification with pentaerythritol. Quimica Nova. 2008;31(8):2076-2082.

[8] Dave VJ, Patel HS. Synthesis and characterization of interpenetrating polymer networks from transesterified castor oil based polyurethane and polystyrene. Journal of Saudi Chemical Society. 2017;21(1):18-24.