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2K Ambient-Curable, Crash-Toughened Structural Adhesive - From formulation trade-offs to OEM-level performance.

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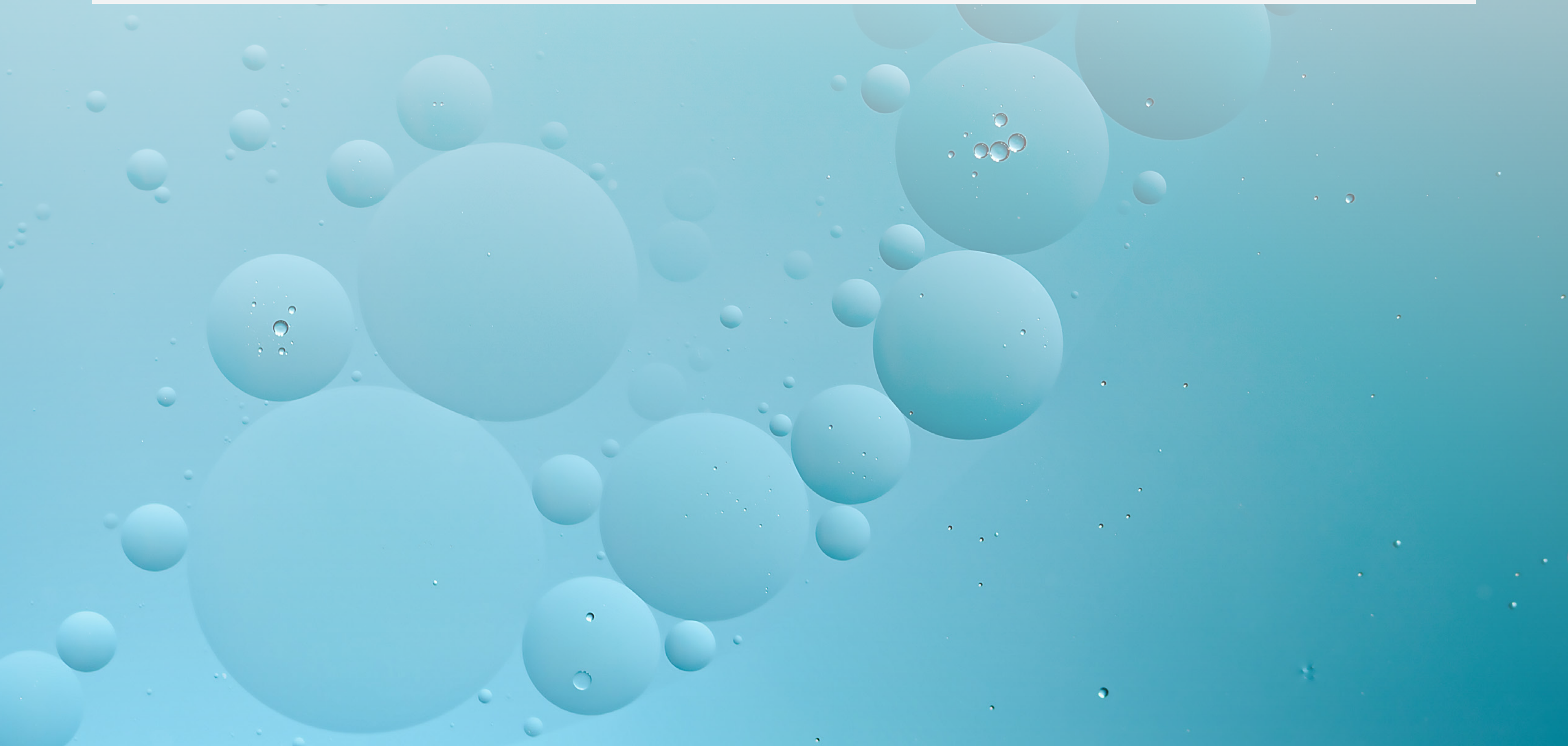
ABSTRACT

Developing two component crash-toughened structural adhesives presents a common materials challenge as the balance of multiple performances is not easy to achieve. High impact resistance usually requires toughening mechanisms provided by the combinations of many high viscosity ingredients and limits the dispensability of the adhesives, while the low viscosity of the material, which is essential for dispensing and surface wetting, always comes with the compromises of toughness and environmental stability. The challenges are further addressed when there is a need for ambient condition curing and tolerance for minimally prepared surfaces, for example, dirty or oily metals.

This paper describes the formulation strategy for a 2k ambient-curable, crash-toughened structural adhesives that can successfully balance the requirements. It demonstrates a unique toughening mechanism, optimized resin-curative structure and delivers a product that presents high mechanical strength, impact resistance, excellent fatigue resistance and environmental resistance with the relatively low viscosity. This formulation method enables effective energy dissipation under impact and achieves the ability to adhere to oily metals and reduces the need for aggressive surface preparation and is designed to be suitable for user applications under ambient conditions such as automotive, automotive repairs and constructions etc. This study offers an insight into next-generation ambient-cured structural adhesives.



01. INTRODUCTION

Structural adhesives used in transportation and industrial applications must withstand complex loading environments that include static stress, dynamic impacts, cyclic fatigue, and long-term environmental exposure. Heat activated epoxy adhesives have historically dominated these applications due to their ability to achieve high crosslink density, strong adhesion to oily metals, and robust crash toughening behavior. Elevated temperatures promote resin mobility, enhance wetting, facilitate oil diffusion, and activate phase separating tougheners such as CTBN and urethane-based modifiers.

Ambient curable systems, by contrast, must achieve comparable performance without the benefit of thermal activation. This imposes several intrinsic limitations:

- Reduced crosslink density
- Incomplete activation of phase separating tougheners
- Limited wetting on oily or contaminated substrates
- Reduced environmental resistance
- Viscosity constraints that restrict toughener loading

Despite these challenges, ambient curable adhesives are increasingly required in automotive repair, EV battery bonding, marine structures, commercial vehicles, and low energy manufacturing environments. These applications demand materials that cure reliably at room temperature while delivering mechanical performance traditionally associated with heat activated systems.

The adhesive (L&L Bond XP-K435) described in this paper was developed to address these constraints through a formulation strategy that balances moderate viscosity for dispensability, toughness, surface tolerance, and environmental durability. The following sections describe the molecular design, toughening mechanisms, and performance validation that enable this advancement.

CHEMISTRY AND FORMULATION DESIGN

The formulation of XP-K435 is rooted in a multi-component formulation designed to achieve high mechanical performance and crash toughness. It inherited the toughening mechanism from a high viscosity adhesive XP-K436 which incorporates a blend of epoxies including silane-modified epoxy for improved adhesion, phase-separated tougheners for impact resistance, flexibilizers and chain extenders for improved flexibility. The addition of various diluents has enabled this formulation to maintain high performance and reduce the viscosity for easy dispensing.

1. Reactive diluents

Reactive diluents participate in crosslinking reactions, modifying network architecture and increasing flexibility. They reduce viscosity while maintaining mechanical integrity. This incorporation can increase the flexibility of the cured adhesive by reducing overall network rigidity and enabling greater segmental mobility within the crosslinked structure. As a result, the use of reactive diluents can contribute both to improved handling characteristics prior to cure and to enhanced toughness, ductility, and strain to failure in the final cured material. The figure below shows the effect on wedge impact peel resistance with the addition of different types of reactive diluents.

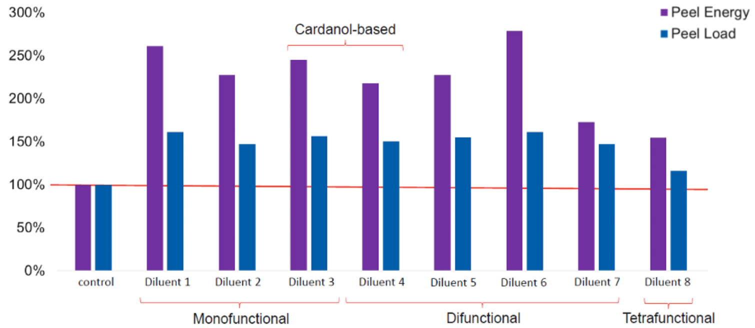


Figure 1. *wedge impact performance with different reactive diluents*

2. Non-reactive diluents

The addition of non reactive diluents can beneficially reduce the viscosity behaving similar to the reactive diluents. Because these diluents do not chemically participate in the curing reaction, they remain physically dispersed within the polymer matrix and contribute to the creation of additional free volume upon cure. The presence of this free volume can reduce network packing density and increase the mobility of polymer segments, which can enable localized deformation and small-size yielding and enhance the crash toughness of the cured adhesive. The figure below shows the effect on wedge impact peel resistance with the addition of different types of non-reactive diluents.

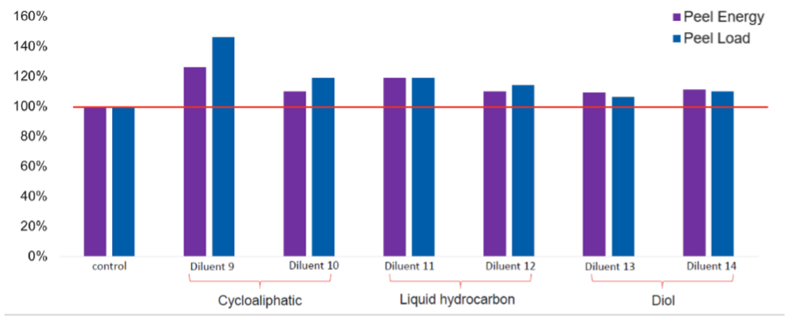


Figure 2. *wedge impact performance with different non-reactive diluents*

3. Synergistic effects

While each diluent type individually provides moderate or minimal improvements in impact resistance with its own mechanism, the combined use of both produces a significantly greater enhancement in wedge-impact peel load and energy, demonstrating a cooperative effect in increase chain flexibility while simultaneously increasing free volume. This synergy arises from the combination mechanisms of the diluents: reactive diluents add flexible segments into the network through crosslinking and reduce rigidity, whereas non-reactive diluents introduce physical plasticization that promotes localized yielding.

	No diluents	Reactive diluent	Non-reactive diluent	Both Diluents
Wedge impact[1] peel strength	21.1 N/mm	21.4 N/mm	19.3 N/mm	27.0 N/mm
Wedge impact peel energy	5.8 J	6.9 J	4.9 J	10.1 J
Lap shear[2] strength	23.2 MPa	22.6 MPa	24.1 MPa	20.4 MPa
T-peel[3] strength	5.3 N/mm	5.2 N/mm	5.3 N/mm	5.3 N/mm
Tensile Modulus	951 MPa	727 MPa	1079 MPa	767 MPa
Tensile strength	13.8 MPa	11.2 MPa	14.8 MPa	14.1 MPa
Tensile strain	8.5%	36.5%	7.4%	38.5%
Tg Tan delta	67.1°C	61.0°C	66.9°C	57.4°C

1) 0.030” EG60, test speed: 2 m/s, drop weight 25 kg, bondline 0.25 mm
2) 0.030” EG60, test speed:10 inch/min, bondline 0.25 mm
3) 0.060” EG60, test speed: 2 inch/min, bondline 0.25 mm

Table 1. *performance of formulations with different combinations of diluents*

PERFORMANCE AND BENCHMARKING

XP-K435 exhibits high mechanical strength and crash toughness, and the data is shown in the table below with performance from other competitors' products on the market. It shows the highest wedge-impact peel load and energy absorption, indicating significantly better crash-durability, and highest retention after environmental exposure. XP-K435 also delivers the highest fracture energy and fracture load, highlighting its strong resistance to crack growth under impact.

Side-by-side testing by L&L		XP-K435	Competitor 1	Competitor 2
Wedge impact[4] 22°C	Avg peel load	27.1 N/mm	21.2 N/mm	17.9 N/mm
	Energy	11.7 J	6.7 J	4.5 J
Fracture energy G1c		2974 J/m²	2376 J/m²	–
Fracture load		2018 N	1804 N	–
T peel strength[1]		5.9 N/mm	6.8 N/mm	3.0 N/mm
Lap shear strength[2]		21.3 MPa	20.5 MPa	28.7 MPa
Lap shear strength on oil[3]		11.0 MPa	12.8 MPa	7.4 MPa
Lap shear retention after 14 d Humidity exposure[5]		108%	59%	72.1%
Lap shear retention after 14 d Salt spray exposure[6]		87%	68%	68.7%
Tensile Modulus		969 MPa	1112 MPa	2742 MPa
Peak stress		13.8 MPa	20.2 MPa	35.9 MPa
Elongation		34.3%	28.8%	2.1%
Tg*		46.8°C	54.1°C	61.5°C
Peak of tan delta		62.6°C	69.2°C	74.3°C
Open time (10g/3mm) min		60 min	1 h 30 min	1 h 45 min
Fixture time (0.5 inch overlap, 0.25 mm bondline,1 kg weight)		4 h 45 min	3 h 40 min	8 h

1) 0.030" EG60, test speed:10 inch/min, bondline 0.25 mm
2) 0.060" EG60, test speed: 2 inch/min, bondline 0.25 mm
3) 0.060" stainless steel, test speed: 2 inch/min, bondline 0.25mm
4) 0.030" EG60, test speed: 2 m/s, drop weight 25 kg, bondline 0.25 mm
5) 104°F and 100%RH
6) 95°F with 1-2ml NaCl solution, PH is 6.5-7.2

* ASTM D7028-07.

Table 2. *test performance of XP-K435 and competitor products*

In automotive and structural bonding applications, fatigue resistance is critical because joints are subjected to millions of cyclic loads over the service life. XP K435 demonstrates outstanding fatigue resistance compared with both competitor adhesives. It is the only material to maintain cohesive failure (CF) throughout all tests, indicating strong internal network integrity. XP K435 also delivers the highest cycle counts by large margins, achieving up to 3,984,499 cycles at 40% load.

Fmax load	70%	60%	50%	40%
XP-K435 failure cycles	14,312 Cohesive failure	66,560 Cohesive failure	224,423 Cohesive failure	3,984,499 Cohesive failure
Competitor 1 failure cycles	12,101 Adhesive failure	37,282 Adhesive failure	20,079 Adhesive failure	422,536 Adhesive failure
Competitor 2 failure cycles	–	1,920 Adhesive failure	140,625 Adhesive failure	168,548 Adhesive failure

Table 3. *fatigue test results*

CONCLUSION

The results demonstrate that the historical performance gap between ambient curable and heat activated adhesives can be significantly narrowed through advanced formulation engineering. The synergy between reactive diluents and non-reactive diluents enables a balanced performance envelope that improves the crash-toughness and reduces the viscosity at the same time and meets OEM requirements while curing under ambient conditions.

This work presents a next generation 2K ambient curable structural adhesive that delivers high crash toughness, strong adhesion to oily metals, excellent environmental durability, and consistent fatigue resistance — all at a viscosity suitable for industrial dispensing. The formulation strategy outlined here provides a pathway for future development of ambient curable adhesives capable of meeting the demands of automotive, EV, repair, and construction applications.

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Dr Ziyan Li is a Scientist at L&L Products, where she develops ambient-temperature curable structural adhesives and sealing materials for automotive and industrial applications. Her work focuses on formulation design, rheology control, and structure–property relationships to address challenging performance trade-offs such as impact toughness, fatigue resistance, environmental durability, and processability under real-world repair conditions.

She leads multiple material development programs spanning formulation, processing, mechanical testing, and failure analysis. Ziyan earned her Ph.D. in Polymer Engineering from The University of Akron, where her research emphasized morphology–property relationships in polymer blends, smart materials, and rheological behavior.

She also holds a Master's degree in Polymer Engineering doing research related to synthesis and formulation of a high-temperature application powder coating. Her technical expertise includes X-ray scatterings, thermal and mechanical characterization, processing and advanced rheological analysis.

Ziyan has presented her research at many national conferences and brings a strong combination of fundamental polymer science and applied materials engineering to structural adhesive development.

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