ADHESIVES FOR LOAD-BEARING TIMBER STRUCTURES – CLASSIFICATION AND PERFORMANCE

Hexion Specialty Chemicals Limited, New Zealand
Email: scott.earnshaw@hexion.com, mark.nowicki@hexion.com, clyde.campbell@hexion.com

ABSTRACT

Adhesives for load-bearing timber structures should be chosen considering the environmental conditions in service, the timber species, the preservative used (if any) and the production methods. The environmental impact of the adhesive may also be a consideration. Finally, compliance with relevant standards, especially where conformance to standards is stated or implied, is essential to mitigate risk for all interested parties.

Resins based on formaldehyde chemistry are the only adhesives that meet the current standard AS/NZS 4364:1996 ("Adhesives, phenolic and amino plastic, for load-bearing timber structures – Classification and performance requirements") [1]. Resorcinol formaldehyde, phenol-resorcinol formaldehyde and tannin formaldehyde adhesives are also the only adhesives that are compliant with Service Class 3 (exterior conditions where the ambient moisture content can be greater than 18%) conditions as specified in the New Zealand and Australian standards for Fingerjointed Structural Timber and Glued Laminated Structural Timber [2, 3, 4, 5]. Indeed, standards for structural timbers around the world have been developed based on the performance of formaldehyde-containing adhesives.

INTRODUCTION

The function of a wood adhesive is to bond two or more pieces of timber together. If the resulting timber member is to be used for load-bearing (i.e. structural purposes) a structural adhesive must be specified.

A structural adhesive must be both capable of withstanding a continuous load with minimal deformation or creep and be durable for the life of the structure as defined in the building codes. The New Zealand and Australian production standards for fingerjointed structural timber and glued laminated structural timber identify the key considerations when choosing an adhesive; namely the environmental conditions in service, the timber species to be used, the preservative used (if any), the production methods and the relevant structural adhesives standard [2, 3, 4, 5].

Historically formaldehyde-based resins have been the adhesive of choice for all such structural timber applications. The performance of formaldehyde-based resins has been proven and documented for over 70 years and has set a very high performance benchmark that the ultimate consumer can have confidence in.

Significant technical and environmental developments have also been made with formaldehyde-based adhesives to deliver cost and production efficiencies and reduce safety, health and environmental impacts throughout their life cycle. As a result of all these features, formaldehyde-based resins offer manufacturers and consumers well-proven performance with recognised failure modes and risk profile.

This is especially important to producers of structural timber elements who understand the risks and potential liability associated with failure. The dominance of formaldehyde-based adhesives is highlighted by the current New Zealand and Australian Standard relating to Adhesives for Load-Bearing Timber Structures which specifies that only formaldehyde-based, thermoset resins comply.

In more recent years, alternative adhesive technologies, historically only suitable for non-structural applications, have advanced and in some cases may provide a viable option for structural timber members. Adhesives such as aqueous polymeric emulsions (API/EPI), isocyanate based polyurethanes and melamine hybrid based adhesives are some of these new adhesive types.

Because this area of technology is advancing so rapidly, the challenge is to determine which of these new adhesive products are suitable for which applications. The challenge is compounded by the fact that there is limited real life data to confirm their performance in situ and, unlike formaldehyde-based phenolic adhesives, the formulations of these new adhesives have changed significantly over recent years. This lack of long term performance data has led to restrictions in some cases. For example, in Japan, API/EPI adhesives can be used, but only in small dimension structural laminated elements.

This article discusses existing structural timber adhesive options, the adhesives specified by the standards for different climatic conditions, and the relative adhesive performance on several key criteria. Although the adhesives discussed are sometimes used for other structural timber products (i.e. engineered wood products such as LVL, plywood and particularly I-beams), this discussion focuses on the bonding of timber to produce structural fingerjointed and glued laminated timber.

DIFFERENT ADHESIVE TYPES

Formaldehyde-based adhesives are synthetic resins derived from a condensation reaction involving formaldehyde. The formaldehyde adhesive family has historically been further broken down into two groups – phenolic and amino plastic.

Phenolic resins are defined in the applicable standard as "a synthetic resin derived from a condensation reaction between a phenolic compound (eg. phenol, cresol, xylenol, resorcinol) or a mixture of phenolic compounds with an aldehyde (eg. formaldehyde, furfuraldehyde) or a mixture of aldehydes" [1]. This group includes:

- resorcinol formaldehyde (RF)
- phenol-resorcinol formaldehyde (PRF)
- tannin formaldehyde (TF)

Amino plastic resins are defined in the standard as "a synthetic resin derived from a condensation reaction between a synthetic compound containing amino groups (eg. urea, thiourea, melamine) or allied compounds alone or in combination, with formaldehyde" [1]. This group includes:

- melamine-resorcinol formaldehyde (MRF)
- melamine-urea formaldehyde (MUF)
- urea formaldehyde (UF)

All of these formaldehyde-based resins are thermosetting adhesives. Thermosetting adhesives are materials that either have or will undergo a chemical reaction by the addition of heat or catalysts, leading to a product with a relatively infusible, or inert, state.

Historically, phenolic resins were used for exterior or harsh climatic conditions while the more cost effective amino plastic resins were specified for stable and moderate interior conditions However, just as the alternative resin technologies have developed, so too have the amino plastic resin technologies, specifically melamine-based resins. This means that the use of amino plastic resins in the future could be expanded.

It should be noted that the potential use of urea formaldehyde resins for structural purposes is minimal due to hydrolysis of the bonds over time leading to a potentially unacceptable risk profile and poor performance. For these reasons, urea formaldehyde resins are not discussed further in this article.

The isocyanate-based family of adhesives uses either monoisocyanate or diisocyanate as a raw material. These products have been used for many years for non-structural applications. They are often perceived to be more user friendly during manufacture of the timber members and, in recent years, have started to be used more widely for specific structural applications. Within this family there are also two distinct adhesives types.

Aqueous Polymeric Isocyanate (API) – also often called Emulsion Polymer Isocyanate (EPI) – adhesives are two component adhesives which involve reaction of a water based emulsion with an isocyanate hardener. The argument over whether these adhesives are truly thermosetting or thermoplastic and, therefore, soften on heating is still debated. Performance-based testing of APIs/EPIs is also being implemented worldwide to determine their suitability for specific applications.

Polyurethane (PUR) adhesives are typically manufactured by crosslinking a polyol (usually glycol) with diisocyanate to form an isocyanate-terminated urethane [6]. PUR adhesives are available in a range of grades. The most common are single-component PUR (1K PUR) and two-component PUR (2K PUR). Polyurethane adhesives may be either thermoplastic or thermosetting depending on how the adhesive is formulated.

Although the chemistries of both the formaldehyde and isocyanate families of adhesives are quite distinct, they do share core raw material sources. Both originate from natural gas and oil. Formaldehyde is also common to both chemistries as a chlorinated formaldehyde derivative is used in the manufacture of isocyanate. In these times of food miles and labelling, it is correct to say that within New Zealand formaldehyde-based resins would be labelled "made locally from imported ingredients" whilst API's and polyurethanes would be labelled "imported".

COMPLIANCE WITH THE STANDARDS

All adhesives used for bonding structural fingerjointed and/or structural glue laminated timber must currently comply with the joint Australian / New Zealand standard AS/NZS 4364:1996 "Adhesives, phenolic and amino plastic, for load-bearing timber structures – Classification and performance". AS/NZS 4364:1996 establishes a classification for formaldehyde-based adhesives according to their suitability for use for load-bearing timber structures in defined climatic exposure conditions. It also specifies performance requirements for such adhesives used in the manufacture of load-bearing timber structures [1]. Adhesives are classified as either Type I or Type II by the standard according to their suitability for use in the climatic conditions given in Table 1.

As mentioned above, the historical dominance of formaldehyde-based adhesives means that only formaldehyde-based resins comply with AS/NZS 4364:1996. In recent years, it has been agreed by nearly all interested parties that the withdrawal of AS/NZS 4364:1996 is desired and appropriate and that it should be replaced with a performance based standard.

To this end, an interim standard was developed -- AS/NZS 4364(Int):2007. This interim standard also aimed to classify adhesives as either Type I or Type II according to their suitability for use in climatic conditions as identified in the current standard. It had the advantage of allowing a range of adhesive technologies to comply with each condition and was based upon performance. However, the standard also allowed adhesive manufacturers to choose from optional test methods for various adhesive properties in

Table 1. Adhesive types for use in different climatic conditions as specified in AS/NZS 4364:1996

Temperature	Climatic equivalent to *	Examples	Adhesive Type
> 50°C	Not specified	Prolonged exposure to high temperature	I
≤ 50°C	> 85% r.h. at 20°C	Full exposure to the weather	I
	≤ 85% r.h. at 20°C	Heated and ventilated building. Exterior protected from the weather. Short periods of exposure to the weather.	II

* 85% r.h. at 20°C will result in a moisture content of approximately 20% in softwoods and most hardwoods and somewhat lower moisture content in wood-based panels.

order to qualify their adhesives [7]. This was the result of a compromise between the European and North American standards and their associated test methods which differ, in some cases significantly. These optional test methods potentially introduced a high level of risk as adhesive manufacturers could choose to test their adhesives to the lower, or easier, standard. No research has been completed to confirm the impact of this on the performance of glued load-bearing timber structures. At the time of writing there has been no progress in implementing AS/NZS 4364(Int.):2007 to full standards status. Until a new adhesive standard is developed and published, manufacturers of fingerjointed structural timber and/or glued laminated structural timber products manufactured in accordance with AS 5068:2006, or AS/NZS 1491:1996, or AS/NZS 1328:1998 must ensure the adhesives they use comply as summarised in Table 2.

Careful consideration must be taken when comparing structural timber adhesive standards used in other countries. A close study of how these standards correlate with others, such as the production standards, should be taken before adopting outcomes into our own markets, as the risks can be very different. For example, in Europe there is a very stringent approach to standards and tight control on correct use of the final product. This is evidenced in Germany where continuous camera monitoring of glue spreads is a requirement of the structural fingerjointing standard, a legal document, along with very strict auditing of manufacturing plants. Such tight regulations help maintain product quality and assist in minimising the risk of product failure.

THE BUILDING CODES AND STRUCTURAL PERFORMANCE

The Building Codes of Australia and New Zealand are over-arching documents which regulate building design and construction. The New Zealand Building Code specifies that structural building products are required to have at least a 50 year life. The Australian Building

Table 2: What the standards specify - Adhesive types for given service conditions (Normative)

			Service Class		
		Description	1	2	3
			Interior dry	Interior - Humid, exterior protected	Interior - Hot and humid, exterior exposed
		Timber e.m.c	≤ 12%	≤ 18%	> 18% untreated timber > 20% multi-salts treated softwoods
		Adhesive*	Type I or Type II	Type I or Type II, provided the temperature remains below 50°C**	Type I
Adhesive Types Allowed	AS/NZS 1491:1996	Fingerjointed Timber NZ	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde	Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde
	AS 5068:2006	Fingerjointed Timber Australia	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde
	AS/NZS 1328:1998	Glued Laminated Timber NZ and Australia	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde	Melamine-urea formaldehyde Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde	Tannin formaldehyde Phenol-resorcinol formaldehyde Resorcinol formaldehyde

* Adhesives should meet the test requirements for Type I or Type II as specified in AS/NZS 4364:1996.

** Evidence suggests that above 55°C the long term integrity of the wood itself will be compromised.

code also indicates a 50 year life for structural timber products. Formaldehyde-based phenolic type adhesives have historic and real-life data which demonstrates compliance. This proven performance is not reliant on short term modelled data. This information inherently reduces the risk and potential legal liability to the manufacturer in these times where building products durability is being questioned with 'Leaky Homes" and framing timber strength issues are still in the headlines.

DURABILITY

The durability of an adhesive bond is it's resistance to deterioration in any given environmental or service condition. Although the amount of glueline stress depends on a range of factors including the wood species being adhered, the pH of the glueline and the wood, any chemical treatments used and the load applied to the glueline, the most significant impact is variation in the timber moisture content caused by fluctuating or harsh climates. In fact, moisture variation of the timber is the most common reason for glueline or adhesive failure in service.

The durability of some resins is better than others. Phenolic resins are formed via an irreversible cross-linking reaction. They also have a rate of expansion and contraction similar to solid wood. This makes them an excellent adhesive for all applications. Amino plastic resins are generally made by a reversible crosslinking reaction. This reaction can sometimes be reversed by moisture and/or acid (referred to as hydrolysis) which can result in bond failures. Urea formaldehyde resins are prone to hydrolysis and therefore, are largely restricted from structural use these days. Melamine formaldehyde resins, however, have good resistance to hydrolysis as well as a rate of expansion and contraction similar to solid wood. API adhesives have been shown to perform satisfactorily for at least twenty years in moderate service environments. Polyurethane technology is a more recent development, and European data indicates good performance over fifteen years in moderate conditions.

Of course, the smaller the timber dimensions the larger the potential moisture variation between pieces will be and, therefore, the more stress on the glueline. This is just one of the reasons that durability data from Europe, where large dimension timber products are common (and therefore moisture variation is less), may not be relevant to New Zealand or Australia where much smaller products are used for an equivalent purpose. The United States and Canada, which also use relatively small cross-sectional beams, have adhesive standards in place that effectively ensure that the adhesive glueline is at least as durable as the timber itself. The applicable standards ASTM D2559-04 and ASTM D3434-00(2006) in the US and CSA O112.9-04 in Canada have been passed by very few adhesives apart from phenolics [8, 9, 10]. This contrasts to the European standard EN301 which has passed a wide range of adhesive types for full exterior use.

HEAT AND FIRE PERFORMANCE

In recent years, the fire performance of structural timber products, and more specifically the adhesives used to bond these products, has come under the spotlight largely driven by North American fire fighters and building code agencies. In 2006, the North American timber industry performed full-scale fire resistant tests on wood-frame wall assemblies and found that fingerjointed studs did not perform on a par with equivalent solid-sawn studs as had long been accepted by building codes [11].

This led the Forintek researchers to develop a small scale elevated temperature tension test to further study the performance of a range of adhesives. The researchers quickly found that the PRF and melamine-based adhesives outlasted the two hour testing period. In fact they frequently lasted three to four hours before the test was stopped without failure occurring. Even when failure did occur with melamine and phenolic samples, there was usually a significant amount of wood failure. On the other hand, the testing of seven different polyurethanes resulted in all samples failing within a 30 minute timeframe, and with little or no wood failure. The study concluded that there is considerable variability in the elevated temperature performance of different adhesives and that the adhesive used in fingerjointed studs has a direct impact on the fire-resistance of the wall assembly.

Since then, the American Lumber Standards Committee (ALSC) has developed a heat-resistant adhesive (HRA) labelling system for products meeting fire-resistant qualification criteria which allows easy identification of fire-rated assemblies by building officials.

So, while phenolic resins are among the most thermally stable polymers known to exist (evidenced by their extensive use in the manufacture of brake linings, high temperature composites, grinding wheels and flame retardant materials), and amino plastic resins perform similarly under load-bearing conditions, the variation in heat and fire resistance of newer structural timber adhesives used in load-bearing structures has caused their overall suitability to fall into question.

There are arguments, in Europe, that such exceptional heat stability is not required by adhesives, as in a fire situation the char layer may act to insulate the internal timber. However, in Australasia where the cross-sectional size of the timber is much smaller (compared to Europe especially), this argument is less valid. It can be argued that the char layer integrity is compromised by adhesive failure, and the conductivity of the glue itself could transfer heat deterioration. Either way, one would expect that a base requirement for a structural adhesive is that it maintains its integrity at least as long as the wood it joins.

CREEP

Creep is defined as the dimensional change with time of a material under load. Heat or an increase in moisture content typically increases the stress on the load and therefore the deformation. Creep resistance or the ability of an adhesive to resist deformation under load is a key requirement for structural adhesives.

Generally, thermosetting adhesives have excellent creep resistance while thermoplastic adhesives, such as PVAc, have little or no resistance to creep. Phenolic and amino plastic resins both have a well-proven history of creep resistance from sub zero temperatures through to the char point of timber at around 230°C. In fact, AS/NZS 4364:1996 does not even measure creep performance as it is not considered an issue with formaldehyde-based adhesives.

With the possible introduction of alternate adhesive technologies into Australasia for structural purposes, the introduction of a reliable creep standard is also required, especially because many of the API and polyurethane adhesives exhibit thermoplastic tendencies. In Europe, where creep deformation is performed typically at 20°C and then again at 80°C (based on the assumption that this is the maximum temperature building products are likely to be exposed to in the roof space in summer) a range of adhesive types including formaldehyde-based, API and polyurethane have passed. The United States and Canada have implemented standards to ensure bonded timber is in no way inferior to solid lumber and hence perform creep tests at temperatures from 180°C through to 230°C to mimic the char point of timber and ensure the lowest risk profile. These tests are challenging for many adhesives and typically are only passed by phenolic and melamine-resorcinol formaldehyde adhesives.

MARINE AND IN-GROUND CONTACT

Marine and/or in-ground contact situations are arguably the harshest environments that an adhesive can be exposed to. In both of these environments, not only can the timber be fully saturated with moisture but salt exposure is common, swelling the wood cells. This increases the stresses on the gluelines and the surrounding timber which increases the chances of adhesive bond failure, creep and delamination. Phenolic resins are the only adhesive proven in these extreme environments. AS/NZS 4364:1996 does not specifically include any tests for such conditions.

TIMBER TREATMENT

Timber, of course, is not infinitely durable in exterior environments and is invariably treated in some way. Coatings and preservative treatments are necessary to ensure this long term durability. Products bonded with phenolic and melamine based adhesives have proven, long term field performance when exposed to Copper Chromium Arsenic (CCA) and Light Organic Solvent Preservative (LOSP) treatment to the glueline. There is no known published data to show the long term performance for the newer adhesives with the solvents and chemicals used in timber treatment.

New timber treatments also need to be evaluated for glue compatibility. Treatment after gluing means the adhesive is cured and more chemically resistant, but for glued timber products this may result in limited envelope treatment. When full penetration treatment is required, the adhesive needs to bond wood containing the added chemicals and this can interfere with the bond chemistry. Either way, special care and expertise is required to ensure the two chemistries are compatible and the resulting bond durable.

SAFE HANDLING

When using formaldehyde adhesives, the exposure to formaldehyde poses the greatest concern. In 2004, the International Agency for Research on Cancer (IARC) changed the classification of formaldehyde to “a known carcinogen” [12]. While the exposure levels today are significantly lower than the levels reported in the studies referenced by IARC in their decision, lax handling of these adhesives can lead to skin and eye irritation and respiratory complaints.

When using polyurethane adhesives, it is the toxicology of isocyanates that is the primary concern. Repeated exposures to diisocyanates can also lead to respiratory problems (asthma-type symptoms) and sensitisation, while nearly all the monoisocyanates are eye and skin irritants.

With any of the adhesive options, appropriate workplace precautions must be taken to avoid exposure and allergic sensitisation.

EMISSIONS

Formaldehyde emissions from solid wood and in particular from bonded timber have faced increased scrutiny over the years as the public becomes more aware of any possible short and long term health effects of substances in the air we breathe and indoor air quality issues. It is perceived that use of a formaldehyde-based resin will increase such emissions and possibly prevent green labelling of end products. However, even the most stringent global emission standard, the Japanese Industrial Standard JIS A5905 (2003) can be achieved using a variety of formaldehyde-based adhesives. The benchmark JIS A5905 (2003) specifies a mean formaldehyde emission level of 0.3 mg/L (0.08 ppm in air) or less to achieve an F**** rating, similar to the levels specified in the European Super E0. Hexion’s internal research confirms that two to three weeks after manufacture most products made with formaldehyde adhesives will meet F****. This is because there is almost no free formaldehyde in the final adhesive film; the condensation reaction has utilised it effectively. Products made with API and polyurethane adhesives also usually comply with F****.

Adhesive companies globally continue to reduce both the formaldehyde content and emissions of their resin systems. For example, Hexion has recently developed and commercialised a fast curing resorcinol resin system that has 1/20 of the formaldehyde of conventional resorcinol resin systems.

Of course some wood species have naturally high and variable emissions with occasional wood samples testing higher than phenolic glued timber products. It should be remembered that formaldehyde is ubiquitous in nature and background readings in some places can therefore be quite high.

QUALITY CONTROL AND MANUFACTURING OF ADHESIVE JOINTS

This critical topic is large and outside the scope of this article. However, once it has been determined which adhesive will meet requirements, the next step is to ensure that proper factory and quality control procedures, throughout the gluing process, are in place to ensure that the expectations of the standards are met. This is really only possible in a controlled environment with trained and qualified staff (ie in a factory). Site gluing of wood with any adhesive is fraught with traps and dangers that should be avoided at all cost. Whilst the temptation to site glue a scarf or joint can be high, the risks are real and the answer from those with experience is always "Don't do it!".

CONCLUSION

The key to safe structural bonded timber products, such as fingerjointed and glue laminated timber, is an adhesive system with a polymer matrix which remains virtually intact under all exposure conditions (for example: heat, fire, moisture, salt, etc.) In this regard. thermosetting adhesives, such as phenolic resins, are currently unmatched.

Based on the adhesive standard AS/NZS4364:1996, as well as the production standards for structural fingerjointing (AS/NZS 1491:1996 and AS 5068:2006) and glued laminated (AS/NZS 1328:1998) timber, only formaldehyde-based resins comply, and phenolic formaldehyde resins are required in most cases for Service Class 3 conditions.

In developing a new adhesive standard for bonding load-bearing timber products, all performance measures are critical as the cost of failure could be significant both to the manufacturer and end-user. Hexion embraces rigorous testing protocols which ensure interchangeability of bonded timber products with solid lumber whenever possible. Specifying or allowing adhesives that deliver anything less undermines the entire industry's value proposition and potentially opens manufacturers up to liability and public relations issues.

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