SVOA Materials Science & Technology

ISSN: 2634-5331

ScienceVolks
Open Access

Research Article

Adhesive Bonding Systems for Construction and Building Materials

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***Received:** January 12, 2022* ***Published:** February 18, 2022*

Abstract

Adhesives are increasingly being used in the construction and building sector. On the one hand, this concerns dowel reinforcements using chemical anchors. On the other hand, the sealing and repair of cracks in structural components in the construction and building sector are still on the rise. In the field of bonding, the interface is the most critical part of a bonded joint, because it is in this zone that cracks first appear, which in the worst case can spread uncontrollably and lead to total failure of the entire structure. Therefore, it is of immense importance to characterize and investigate this section sophisticated. Since standardized mechanical test methods are not sufficiently capable of doing this, recourse is made to an innovative concept based on fracture analysis. A series of experimental tests were performed to study the adhesive bonding efficiency of different polymeric adhesive systems used for construction and building materials. Novel safety metrics were created and applied to establish a performance rating of the peer group under investigation. Results unveil that bonding efficiency is highly dependent on the chemical basis of the adhesive system applied and thus significantly affects the failure mode to be expected in case of cracking. Furthermore, it was found that only tough polymeric adhesive systems are suitable for bonding construction and building materials effectively and safely for mastering structural bonding challenges well. This can be justified by the fact that such adhesive systems can delay cracks and thus stop them in the best case. On the contrary, due to their strong cohesion, brittle adhesives are not capable to stop cracks from propagating effectively. Furthermore, due to their high cohesive strength, they tend to distract cracks to the substrate if weaker leading to uncontrolled failure of the whole structure. This finding, therefore, leads to the conclusion that brittle, high-strength adhesive systems are not suitable for structural bonding of several building materials such as stone, bricks, marble, concrete, or wood. Only those adhesives are suitable for building materials that can absorb enough fracture energy to prevent a propagating crack for uncontrolled running with the danger of a catastrophic spillover to the substrate structure outside the interface.

Keywords: *Construction and building materials, adhesive bonding systems, structural safety evaluation, adhesive bonding efficiency, peer bonding performance, safety factor, safety premium, adhesive safety ratings.*

Introduction

An extensive literature search revealed that no information is available regarding the structural safety assessment of adhesive sealants to the author's knowledge. While there are publications on bonding cementitious materials adhesively, this is not done with polymeric-based adhesives and sealants, which were used in this study. It is noteworthy to mention, that publications found to deal with either pure concrete-to-concrete bonding, where new concrete layers are applied on top of old ones [1-3]. However, since these are not traditional polymeric adhesive bonds, those works will not be focused on detail. The next major field of research concerns the bonding of fibre composite components for structural external reinforcement of concrete buildings [4, 5]. Most often, this takes the form of mats joined by epoxy resin bonding [6-8]. In addition, there are still studies that deal with the bonding of woods, which is based on polyurethane adhesives [9, 10]. Traditional mechanical test methods, such as the lap-shear test [11-14], pull-off test [15-18], peel-off test [19, 20], and tearing test [21] are used to characterize adhesion and cohesive properties. They are based on linear-elastic continuum mechanics by deriving mechanical stresses as damage criteria. Fracture analysis also already plays a major role, where profound information about the delamination behaviour of a joint through cracking can be obtained [22]. This applies to bonded structures, where traditional standard test methods are not able to provide adequate information on the softening process in the bonded zone [11-21].

This is because the major disadvantage of tensile testing methods is that only a strength value based on the technical stress (tensile strength) is obtained, which, however, only refers to laboratory specimens. Thus, the softening processes of the interface are not fully characterized. Figure 1 shows a compilation of the major drawbacks and pitfalls of the standard test for adhesive bonds and, the lap-shear test [11-14]:

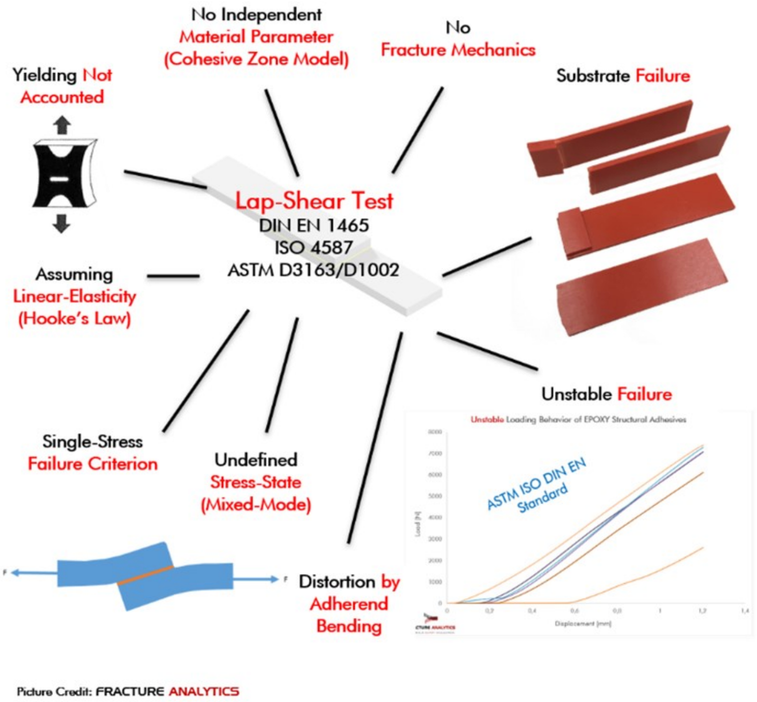

Figure 1: NuOverview of major drawbacks and pitfalls of the lap-shear test [11-14]. Picture Credit [31].

Unfortunately, with the current knowledge of the author, no comprehensive evaluation concept of adhesives for construction and building materials bonding can be found in the literature. That is why a novel study was conducted on different adhesive bonding systems for construction and building materials by applying non-linear plastic fracture analysis [23].

Aims and Scope

This paper aims to highlight those gaps stated above, such as unsuitable test methods for characterizing crack propagation and softening behavior as well as unstable and discontinuous test curves with limited evaluation parameters technical stress based on linear-elastic continuum mechanics [11-21]. For this purpose, a specially developed structural adhesive safety factor and adhesive safety premium were designed to close the economical knowledge gaps on technical product sheets provided by the manufacturer. Furthermore, a mathematical concept was applied to create an adhesive bonding performance index that allows for independent empirical peer ratings of the adhesives under investigation. Experimental tests on ten different polymeric adhesive systems on joints of construction and building materials have been conducted.]]. The results show that only a fraction of the adhesive systems tested is suitable for the structural bonding of such materials. Furthermore, this enables the creation of objective evaluation parameters on a techno-economic basis leading to a significant knowledge gain compared to the manufacturers' technical datasheets.

Evaluated Materials

Table 1 shows a compilation of evaluated polymeric adhesive systems of this study used for bonding construction and building materials. In total, ten adhesives of seven chemical systems were selected. All information was taken from the datasheets of the manufacturers. The candidates were classified by the producers as suitable for joining building materials or at least not declared unsuitable.

Table 1: Overview of evaluated adhesive systems for bonding construction and building materials. Source: [31]

Number	Adhesive System	Notation	Application
1	Acrylic	URF	Plastering
2	Acrylic	MAC	Plastering
3	Silane-Modifed Polymer (MS)	FAF	Construction Adhesive
4	Silane-Modifed Polymer (MS)	FAX	Construction Adhesive
5	Styrene-Acrylic Copolymer	KSB	Construction Adhesive
6	Silicone	SIL	Liquid Sealant
7	Silane-Modifed Polymer (MS)	MSE	Elastic Adhesive
8	Cyanoacrylate/Acrylate Hybrid	HYS	Structural Adhesive
9	Polyurethane	PUV	Vehicle Body Adhesive
10	Epoxy	EPV	Vehicle Body Adhesive

Evaluation methods

1. Fail-Safe Evaluation

The first evaluation principle assesses the so-called *fail-safe behavior* of the adhesive interface during failure. This is evaluated by measuring whether a bonded composite has an unstable and uncontrolled crack propagation or a smooth controllable course. Standardized test methods according to [11-21] tend to test the adhesives unstable and thus falsely label them as brittle. Optimized test equipment makes it possible to determine the actual test curve during softening. Figure 2 shows this principle.

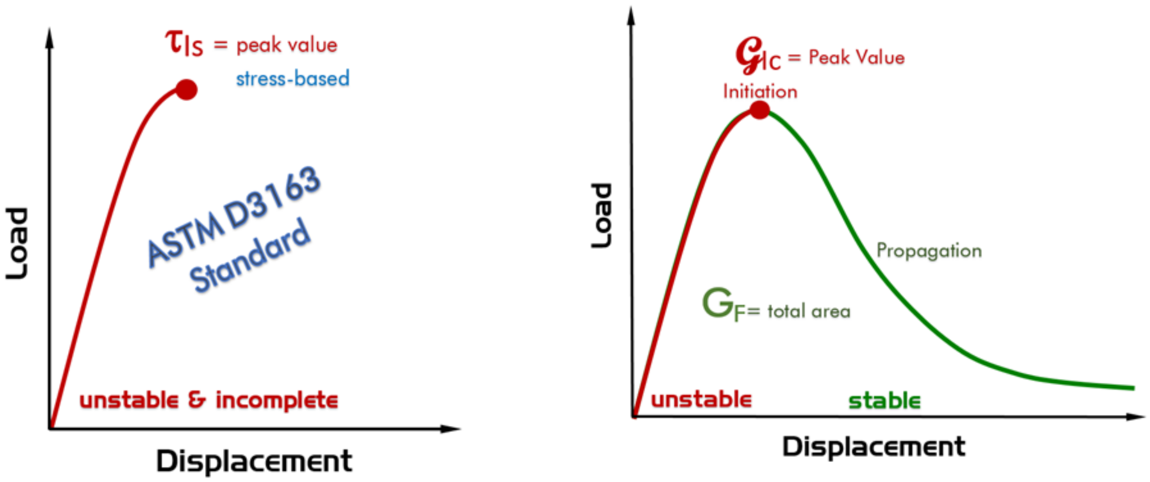

Figure 2: Left: Unstable and incomplete course of a loading curve via lap-shear test [11-14].
Right: Stable and continuous course of a load-displacement diagram via fracture analysis [23].

Picture Credit: [31]

Furthermore, a stable-steady course of a load-displacement diagram is also called *material laws* or *cohesive zone models*. It is obtained by testing a material using fracture analysis under the three possible modes and subjecting it to controlled crack propagation [22]. The fracture energy released during the propagation process and the cohesive stress are measured [23]. These parameters are considered independent material properties, which cannot be said of measured values from tensile test methods (Figure 2, left). A necessary basic requirement for recording fracture-analytical material parameters is the recording of a stable, continuous test curve (Figure 2, right).

2. Adhesion Bonding Quality

The second evaluation methodology concerns the adhesion bonding quality (ABQ) of the interface. Figure 3 shows this principle in detail.

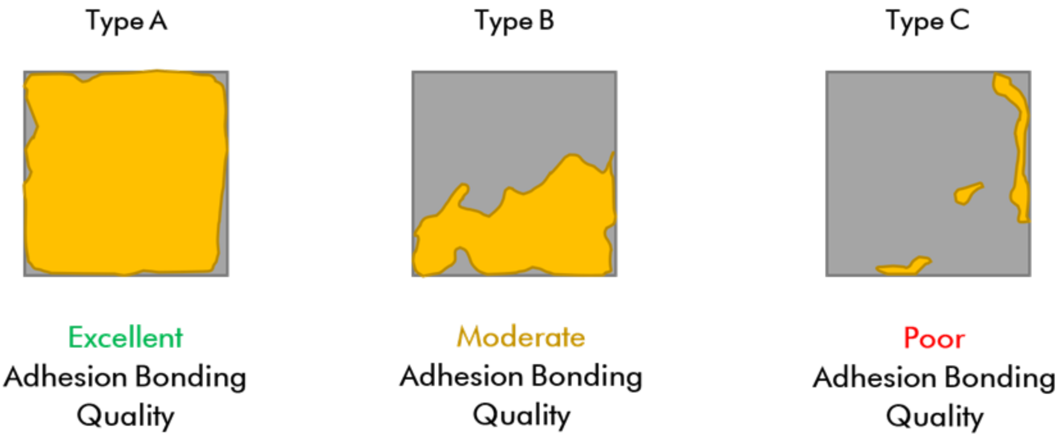

Figure 3: *Overview of three basic types of adhesion bonding quality. Picture Credit: [31]*

3. Structural safety factor

There are well-established and proven approaches widely used in fracture analysis. Regarding which regime holds (linear-elastic or elastic-plastic), the most important criteria are known as G, K, and J [22]. However, there are also approaches in non-linear plastic fracture mechanics, such as the G_F principle of Hillerborg [23]. For the interested reader, further applications of this method are reported for concrete [24, 25], wood [26], adhesives [27-29], and bio-composites [30].

Unfortunately, since the G_F value is a single fracture analysis criterion, other material-specific factors are not fully considered, such as strength and toughness. Therefore, a multi-parameter approach was created, and a single evaluation index was formed using three fracture characteristic values [27]. The benefit of such an approach is an effective and holistic characterization of empirical material properties into one metric, a simpler interpretation of their meaning, and easier presentation of a complex issue for decision-makers. The alternative is offered by the formation of a so-called *structural safety factor* according to [27-30], which is a multi-parameter hybrid metric incorporating several fundamental fracture analytical material properties based on fracture analysis. Equation 1 describes the relationship:

$$S_F = f(G_F \cdot \sigma_c \cdot l_{ch,exp}) \qquad (1)$$

with G_F as the specific fracture energy in [J/mm^2], σ_c the interfacial cohesive strength in [MPa], and $l_{ch,exp}$ as the experimental characteristic length in [mm]. Figure 4 describes these single metrics used to create the safety factor. They represent the size, shape, and course of the stable load-displacement diagram of the adhesive under investigation.

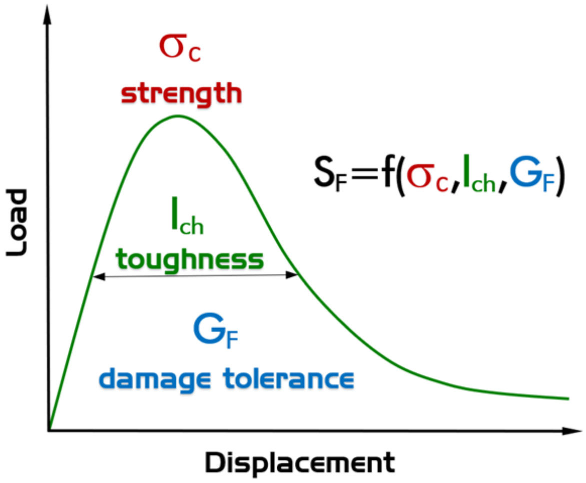

Figure 4: *Schematic illustration of the structural safety factor principle [27-30]. Picture Credit: [31]*

4. Peer bonding performance

Finally, as evaluation metrics have been created, a mathematical value analysis in the form of a peer group evaluation has been conducted. This is accomplished by creating so-called *adhesive bonding performance (ABP)*, which measures the performance of bonding with the inclusion of both, safety costs and bonding safety. This ABP metric enables an empirically valid performance rating. Figure 5 illustrates the basic concept of this mathematical approach.

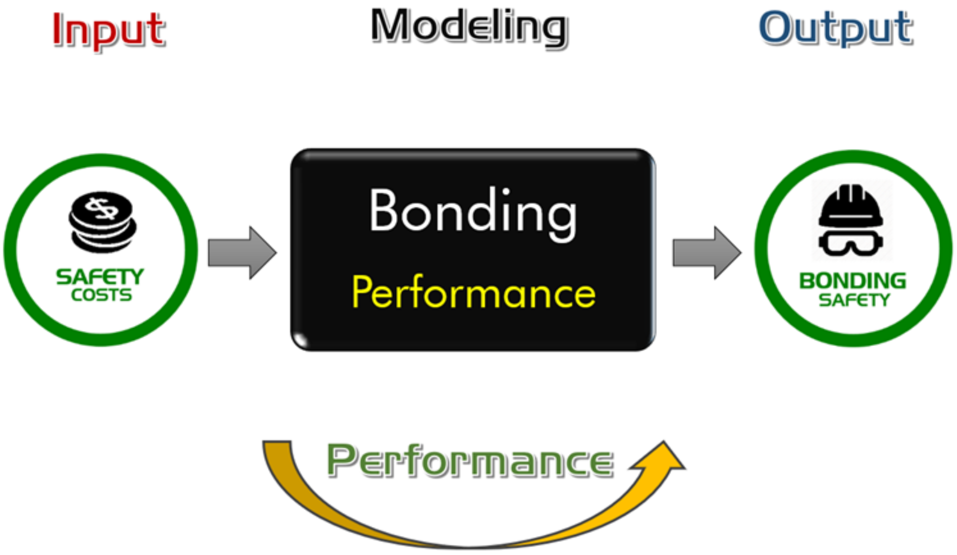

Figure 5: Schematic illustration of characterization of peer bonding performance [29].
Picture Credit: [31]

Results & Discussions

Figure 6 illustrates the peer safety portfolio of the tested adhesive systems for bonding construction and building materials. It takes account of adhesive bonding efficiency, which was formed by adhesion bonding quality as described above, and the safety factor from [27-30]. The different colours represent the structural safety according to the traffic light system highlighting the risk of unstable failure.

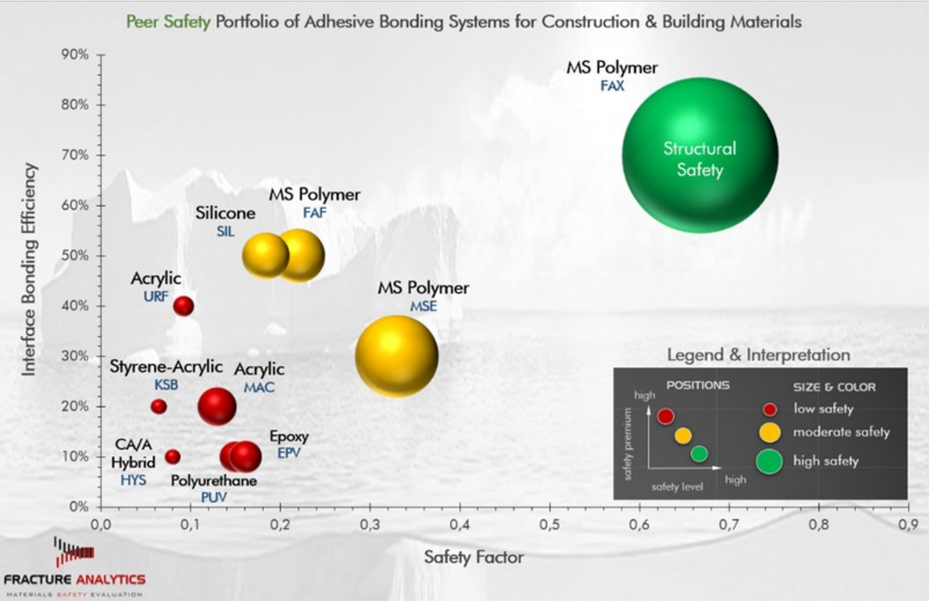

Figure 6: Peer safety portfolio of adhesives systems used for construction and building materials.
Source: [31]

It is noticeable that three clusters have been formed. The first one focuses on two-component structural adhesives of type epoxy (EPV), cyanoacrylate/acrylate hybrid (HYS), and polyurethane (PUV), with basically high strength and low elasticity, especially for metal bonding. However, they exhibit very low adhesion properties to bonded interfaces, which leads to a massive deterioration of structural bonding safety. This fact is expressed by low safety factors ranging from 6.4 % for the SAC-based candidate named KSB up to 16.1 % for the epoxy-based EPV adhesive. Consequently, those candidates are marked up with small red balloons indicating their low bonding safety (high failure risk). Styrene-acrylic and pure acrylic-based adhesives, such as KSB, URF, and MAC, form the second cluster likewise revealing very low values of structural safety and bonding performance. Consequently, they were also marked with small red balloons demonstrating a high risk of unstable failure. The final cluster is formed by silicone (SIL) and silane-modified polymer adhesives (MSE, FAF, FAX). They are marked in yellow and demonstrate adhesive safety factors ranging from 18.3% up to 32.9%. Interestingly, the silane-modified polymer-based adhesive FAX highlights by far the highest bonding performance with a measured bonding efficiency of 70% at a safety factor level of 66.8%.

The explanation for this behaviour lies in the adhesive systems used and their different toughness states. High strength adhesives such as epoxy (EPV), cyanoacrylate/acrylate hybrid (HYS), and polyurethane (PUV) according to table 1 are not able to develop a large process zone (plastic zone) in the interface during the cracking process. This in turn would be necessary to take up enough fracture energy for damping the propagation and prevent unstable failure. Therefore, the crack front is deflected uncontrollably by entering the weaker material, which is the substrate. It leads to *substrate failure* and *interface delamination*, also known as *adhesion failure* (type A), which leads to poor bonding safety. Fig. 7 left illustrates this damage mechanism in detail.

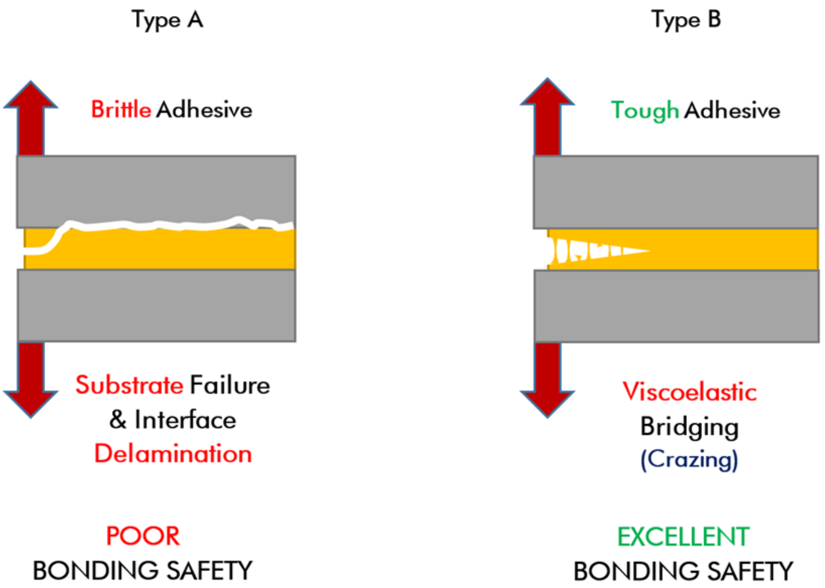

Figure 7: *Overview of failure processes of brittle and tough adhesives on construction and building materials. Source:* [31]

In contrast, silicone (SIL) and silane-modified polymer adhesive sealants (MSE, FAF, FAX) according to table 1 exhibit desirable properties leading to controlled and delayed crack propagation within the adhesive (Figure 7, right). Much higher fracture energy is consumed and secondary shielding effects, such as viscoelastic bridges, allow further crack damping and delay. These properties have a positive effect on the bond safety and thus on the overall structure.

In a final step, the bonding performance of the entire group was calculated, comprising bonding safety, bonding quality, and adhesive safety premium [27-30]. Figure 8 summarizes the total results in a rating and ranking compilation. The coloured distinctions emphasize the risk of unstable failure.

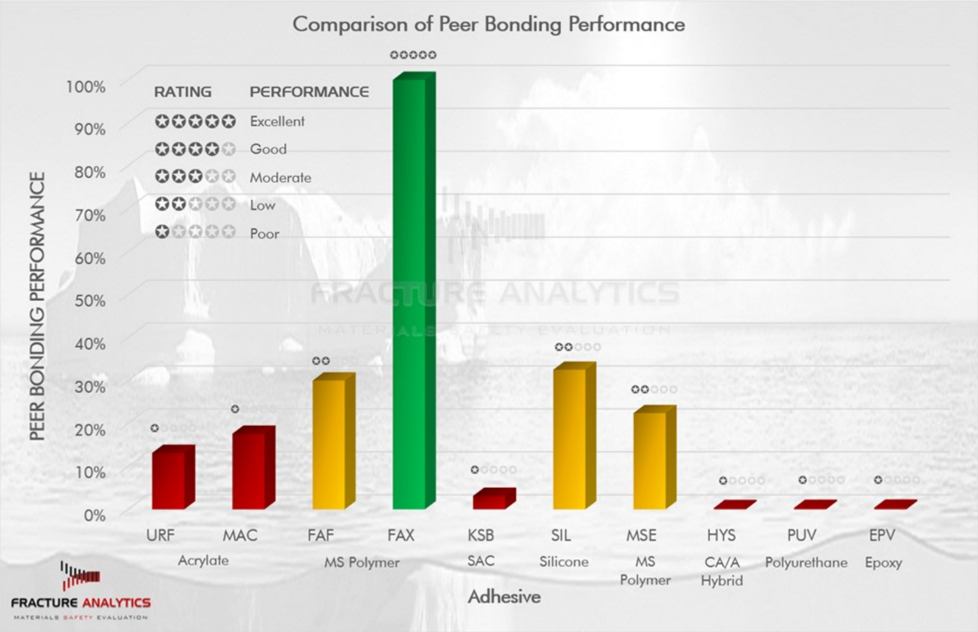

Figure 8: *Peer bonding performance of adhesives systems used for bonding construction and building materials. Source: [31]*

Conclusion

In this study, different polymeric adhesive bonding systems - some of which are commercially used by practitioners and operators in the construction industry - were evaluated for their safety, performance, and efficiency on adhesively bonded joints. This became necessary as technical data sheets and manufacturer' specifications often lack valid data and decision support. Furthermore, the literature has shown that standardized test methods are technologically incapable of providing such information. Therefore, fracture analysis was used as an evaluation tool for the creation of empirical analysis data. By the combination of an innovative test method (G_F principle), multifactorial parameters could be generated. These were then used to create mathematical evaluation models. Ten different adhesive candidates used for bonding construction and building materials-based joints adhesively were tested experimentally. The results of this holistic analysis demonstrated that only tough adhesive systems were able to bond interfaces effectively, safely, and stable enough for mastering structural tasks well. The reason is that adhesive sealants, due to their tough formulation, show positive softening behaviour in terms of crack propagation, crack delay, and crack energy absorption. On the other hand, despite their high strengths, structural adhesives have considerable weaknesses that make them unsuitable for structural bonding of both cementitious and wood-based building materials. Further future research will show how this new finding can and will affect the joining technology of construction and building materials.

Conflict of Interest

The author declares no conflict of interest.

Acknowledgement

The author is thankful to the editors of SVOA Materials Science & Technology for aiding to publish this paper.

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Citation: Brandtner-Hafner MB. “Adhesive Bonding Systems for Construction and Building Materials”. SVOA Materials Science &Technology, (2022) 4:1 Pages: 01-09.