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Structural Safety Evaluation of Polymeric Adhesive Systems for Concrete Bonding

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Abstract **-** Adhesives are increasingly being used in the construction sector. On the one hand, this concerns dowel reinforcements using chemical anchors. On the other hand, the sealing and repair of cracks in concrete structural components are still on the rise. In the field of bonding, the interface between the joined materials is the most critical area. Therefore, it is of immense importance to characterize and investigate this section sufficiently. 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 concrete bonding. 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 a few polymeric adhesive systems are suitable for bonding concrete effectively and safely for mastering structural bonding challenges well.

Keywords**:** Concrete bonding, polymeric adhesive systems, structural safety evaluation, adhesive bonding performance.

1. Introduction
1.1 Basic considerations

Literature review regarding concrete bonding reveals that only a few publications using adhesive systems are found.

Most publications deal with 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 bonding of fiber 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].

Traditional mechanical test methods, such as the pull-off test [7, 8] or shear test [1], are used to characterize the adhesion properties. Also, fracture analysis also already plays a major role, where profound information about the delamination behavior of a joint by means of cracking can be obtained [3]. Unfortunately, with current knowledge of the author, no comprehensive evaluation concept of adhesives for concrete bonding can be found in the literature.

1.2. Aims of paper

This paper aims to highlight those gaps stated above and alternatively provide decision-makers with helpful information for objective adhesive evaluation and selection. 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 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 concrete bonds complete the study. The results show that only a fraction of the adhesive systems tested is suitable for the structural bonding of concrete components. 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.

2. Materials and Methods

2.1. Evaluated materials

Table 1 shows a compilation of evaluated polymeric adhesive systems of this study used for bonding concrete joints. 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 concrete components or at least not declared unsuitable.

Table 1: Overview of evaluated adhesive systems for bonding concrete. Source: FRACTURE ANALYTICS

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

2.2. Evaluation methods

2.2.1. Adhesion Bonding Quality

The first evaluation methodology concerns the adhesive bonding efficiency of the interface. It is used to form the so-called *adhesion bonding quality (ABQ)*. Figure 1 reveals this principle in detail.

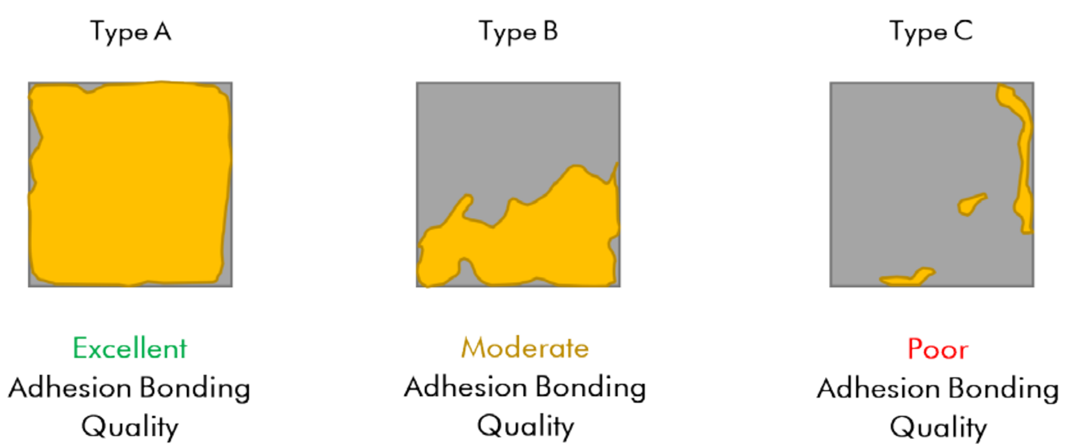

Fig. 1: Overview of three basic types of adhesion bonding quality. Picture Credit: FRACTURE ANALYTICS

2.2.2. Structural safety factor

Basically, there are well-established and proven approaches widely used in fracture analysis. Regarding which regime regime holds (linear-elastic or elastic-plastic), the most important criteria are known as $\mathcal{G}$, K, and J [9]. However, there are are also approaches in non-linear plastic fracture mechanics, such as the G_F principle of Hillerborg [10]. For the interested interested reader, further applications of this method are reported for concrete [11, 12], wood [13], adhesives [14-16], and and bio-composites [17].

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 by means of three fracture characteristic values [16]. 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 [16], which is a multi-parameter hybrid figure incorporating several fundamental fracture analytical material properties based on fracture analysis. Equation 1 describes the relationship:

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

With G_F as the specific fracture energy in [J/mm²], σ_c the interfacial cohesive strength in [MPa], and $l_{ch,exp}$ as the experimental characteristic length in [mm]. Figure 2 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.

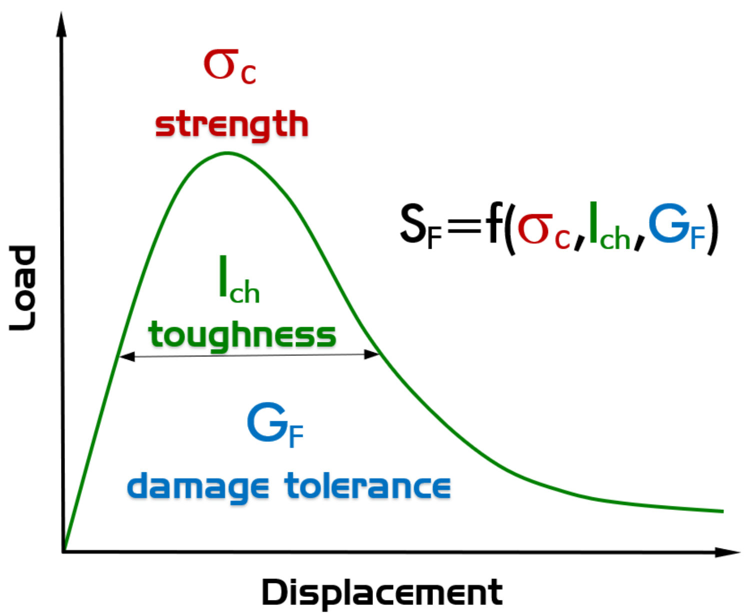

Fig. 2: Schematic illustration of the structural safety factor principle [16]. Picture Credit: FRACTURE ANALYTICS

2.2.3. 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 enables an empirically valid performance rating. Figure 3 illustrates the basic concept of this mathematical approach.

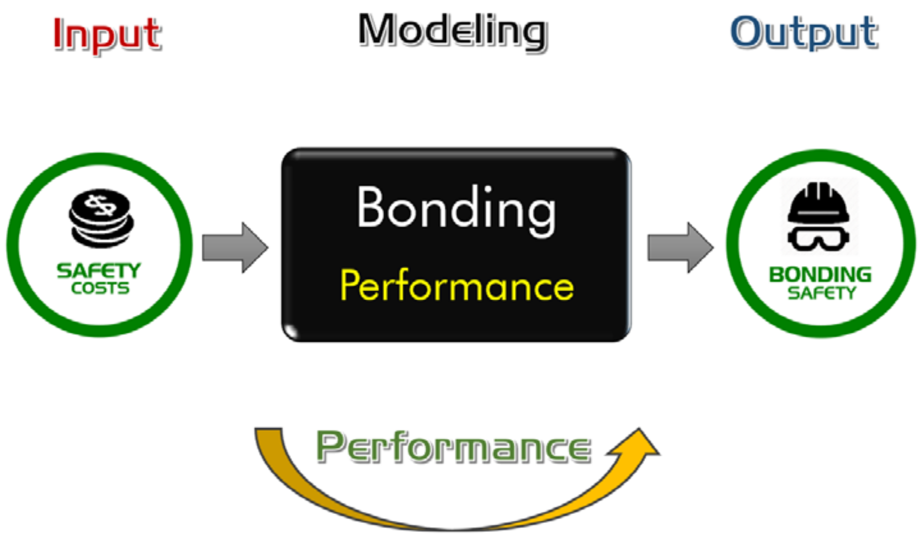

Fig. 3: Schematic illustration of characterization of peer bonding performance [14].
Picture Credit: FRACTURE ANALYTICS

3. Experimental Procedure

3.1 Test method and setup

For this study, MCT specimens were produced via the design of [16, 17], adhesively bonded, and stored for seven days until curing was accomplished. Mode I fracture tests were executed in a quasi-static arrangement according to a setup from [14]. Specific fracture energy G_F, experimental characteristic length $l_{ch,exp}$, and cohesive strength σ_c were measured. The testing procedures were carried out in a laboratory under a standard atmosphere (20◦C, 43% humidity) on a universal testing machine with a maximum loading capacity of 10 kN. The fracture test procedure was conducted in a quasi-static manner for six samples per run at a constant load rate of 2 mm/min. The displacement was recorded separately by using a videoextensometer.

4. Results and Discussion

Figure 4 shows the peer safety portfolio of the tested adhesive systems for concrete bonding. It takes account of adhesive bonding efficiency, which was formed by adhesion bonding quality as described above, and the safety factor from [16,17].

The different colors represent the structural safety according to the traffic light system highlighting the risk of unstable failure.

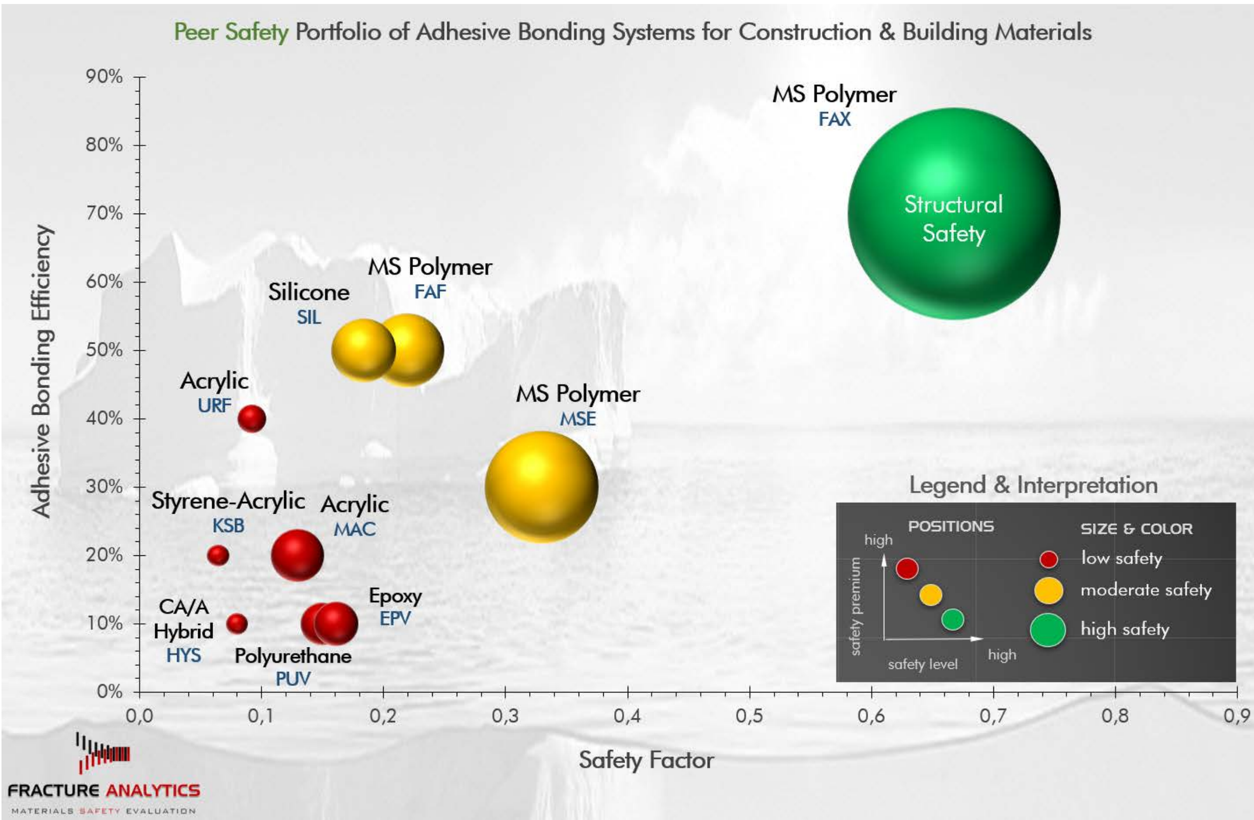

Fig. 4: Peer safety portfolio of adhesives systems used for concrete bonding. Picture Credit: FRACTURE ANALYTICS

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 concrete interfaces, which leads to a massive deterioration of the 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%. This could be explained by a chemical modification in terms of toughening. In a final step, the bonding performance of the entire group was calculated, comprising bonding safety, bonding quality, and adhesive safety premium [16, 17]. Figure 5 summarizes the total results in a rating and ranking compilation. The colored distinctions emphasizes the risk of unstable failure.

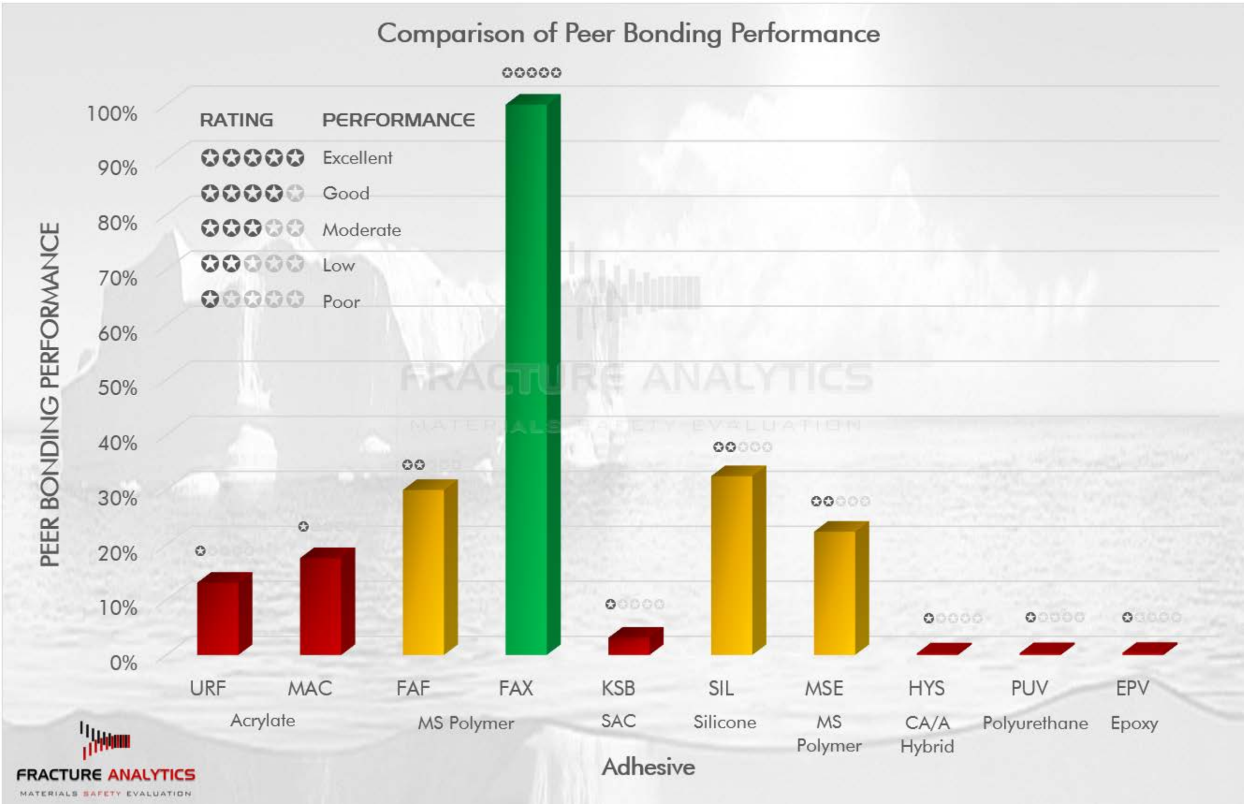

Fig. 5: Peer bonding performance of adhesives systems used for concrete bonding. Picture Credit: FRACTURE ANALYTICS

5. 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 concrete bonds. 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 according to Brandtner-Hafner [14-17] and the G_F method according to Hillerborg [10], multifactorial parameters could be generated. These were then used to create mathematical evaluation models. Ten different adhesive candidates used for bonding concrete joints adhesively were tested experimentally. The results of this holistic analysis demonstrated that only a few adhesive systems were able to bond concrete effectively, safely, and stable enough for mastering structural tasks well. Further future research will show how this new finding can and will affect the joining technology of concrete.

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