THE IMPORTANCE OF SHEAR BOND STRENGTH CHARACTERISTICS OF POLYMER-MODIFIED CEMENT ADHESIVES

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1. INTRODUCTION

With the development of a new generation of polymer-modified cement adhesives, there has been an increasing emphasis on the importance of flexibility and deformation capabilities of these adhesives. While this characteristic has been one of the key elements in the successful application of this type of construction adhesive, the current international standards initiatives to qualify polymer-modified cement adhesives primarily by deformation characteristics do not fully consider the equally important balancing characteristic of high shear bond strength and resulting shear modulus of the adhesives.

The behavior of structural and non-structural adhesive connections has been extensively studied and quantified in mechanical and aerospace applications. However, considerable study and development of quantitative methods for engineering adhered composite tile and stone veneer assemblies in building or infrastructure design remain a priority. This paper explores general adhesive technology theory and engineering analysis to illustrate the importance of high shear strength attributes in polymer-modified cement adhesives, and to demonstrate the need for quantitative design methods for high-performance adhered tile assembly applications such as exterior building facades.

Polymer-modified cement adhesives that are formulated to provide a balanced shear modulus (moderate flexibility with high shear strength) have a 50 year proven empirical history of successful application, as well as basis in established adhesive technology engineering theory that is unique to the specialized field of direct adhered tile and natural stone.

2. BACKGROUND - SHEAR MODULUS OF MATERIALS

Most anyone would have a certain level of discomfort if they learned that a structural engineer guessed the size of steel beams needed for a bridge, with the design rationale based on the fact that steel is simply a very strong material. Yet for some reason, it seems acceptable to select tile adhesives that may be used to adhere tile to a building façade on qualitative characteristics, such as a range of deformation or shear strength alone, without even determining the anticipated movement in the façade substrate, or worse, without knowing or assessing the physical characteristics of the tile, the substrate, or the adhesive used to adhere the tile. This type of "guessing game" can results in significant consequences.

Shear modulus is one of several such quantitative measures of the strength of a material. The shear modulus of a material is essentially a numerical constant that describes its elastic deformation properties, or degree of rigidity, under the application of transverse internal forces. In construction of adhered, composite tile assemblies, such forces would typically result from differential thermal, moisture or structural movement between an adhered veneer material such as porcelain tile, and a typical substrate such as a concrete slab or wall assembly constructed of concrete masonry units.

Physically, deformation can be characterized by a small cubic volume that is slightly distorted in such a way that two of its faces slide parallel to each other a small distance, and two other faces change from squares to diamond shapes (figure 1). The shear modulus is a measure of the ability of a material to resist transverse deformations, but is a valid index of elastic behavior only for small deformations, after which the material is able to return to its original configuration. More flexible materials with large deformations can transition from an elastic state to a plastic state, also known as the material's yield point, resulting in permanent deformation, or fracture under high shear stress.

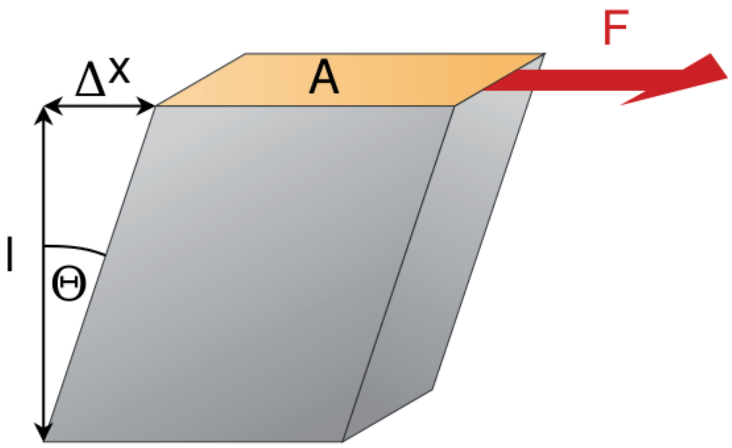

Figure 1. Calculating a material's shear modulus.

In materials science, shear modulus, denoted by the term G, or sometimes S or μ, is defined as the ratio of shear stress to the shear strain. Shear modulus is usually measured in GPa (*gigapascals*) or ksi (thousands of pounds (kips) per square inch):

$$G \stackrel{\text{def}}{=} \frac{\tau_{xy}}{\gamma_{xy}} = \frac{F/A}{\Delta x/I} = \frac{FI}{\Delta x A}$$

Equation 1.

where

$\tau_{xy} = F/A$ = shear stress

F is the force which acts
A is the area on which the force acts

$\gamma_{xy} = \Delta x/I = \tan\theta$ = shear strain

Δx is the transverse displacement
I is the initial length

In order to provide a better understanding of the concept postulated by this paper, consider two different polymer-modified cement adhesives, each conforming to current EN 12004 / ISO 13007-2 tile industry standards for a highly deformable category S2 adhesive, which requires that the adhesive be capable of a transverse deformation of >5 mm (0.2 inches) without adhesion failure. Both adhesives could have the same deformation or strain characteristics (for example 5 mm). However, without knowing the shear stress required to induce such deformation, or the adhesive's shear modulus value, it is not possible to know whether the adhesives have the shear strength resistance to avoid fatigue from cyclical shear stress, or sudden failure from the stress of unrecoverable deformation once the adhesive reaches its "yield point". In other words, both adhesives may comply with the performance standard, but a more flexible adhesive with lower shear modulus and resulting reduced shear strength characteristics may be more susceptible to failure under certain adverse conditions. Therefore, flexibility of polymer-modified cement adhesives alone is not a valid measure of performance when exposed to transverse deformation caused by differential movement between tile and substrates.

3. SHEAR MODULUS OF ADHESIVES

In order to provide a reference framework for comparison of various adhesives, it is helpful to understand the range of flexibility performance for various types of adhesives used in the tile and construction industry.

Adhesives formulated with polyurethane polymers are typically considered relatively flexible adhesives, and exhibit low shear modulus values in the range of 0.05-0.2 Gpa (7.2×10^3 - 2.9×10^4 psi). Adhesives formulated with epoxy resins, typically considered more rigid adhesives, despite having relatively low shear modulus values compared to typical adherends such as porcelain tile, exhibit shear modulus values in the range of 0.2-3.5 Gpa (2.9×10^4 – 5×10^5 psi). Moderately deformable polymer-modified cement adhesives may have a shear modulus in the range of 0.30 Gpa (4×10^4 psi).

By comparison, the value of the shear modulus for aluminum and glass is about 24 Gpa (3.5×10^6 psi), and steel under shear stress is more than three times as rigid as aluminum. On the other end of the spectrum, rubber has a shear modulus of 0.006 Gpa. So in relative terms, polymer-modified cement adhesives generally would be considered materials that exhibit relatively lower shear modulus properties compared with stronger, more rigid materials such as porcelain tile or steel.

4. ADHESIVE CHARACTERISTICS

There are several established test methods for determining the shear modulus and shear strength of adhesives. ASTM D 4027-04 "Standard Test Method for Measuring Shear Properties of Structural Adhesives by the Modified Rail Test"[1], is a test protocol which determines shear strength values for adhesives with a degree of accuracy which allows use in engineering and predicting the characteristics of composite adhered tile assemblies bonded with adhesives. Structural design based on strength of materials principles or the theory of elasticity requires knowledge of the mechanical properties of the adhered materials, including adhesives. By the nature of their use, the most important physical characteristic of an adhesive is shear modulus, and shear modulus determined by both shear strength and shear strain (a.k.a. deformation).

Based on the theory of elasticity, shear modulus of polymer-modified cement adhesives can also be calculated as follows:

$$G_c = \frac{E_c}{2\,(1 + V)}$$

where

G_c= shear modulus of cement.

E_c= modulus of elasticity of cement.

V= Posisson's ratio.

5. ADHESIVE TECHNOLOGY THEORY

An important aspect to consider in assessing compatibility and selection of an adhesive is the difference between the adhered materials' shear modulus characteristics. In an adhered tile assembly, the tile (G_1) has a much greater shear modulus than a cementitious substrate (G_2), therefore the tile-adhesive interface is often more susceptible to concentration of shear stress and potential failure. As a result shear strength becomes the dominant design characteristic, despite the capability of an adhesive to deform. When adhering materials of different compositions and characteristics, research suggests that the shear modulus of an adhesive should be ½ (G_1 + G_2) [2].

So, it is important to select an adhesive with balanced flexibility or rigidity characteristics that are compatible with the adherends, such as the tile and the type of substrate. Construction industry standards such as ASTM standard C0623-05 "Test Method for Young's Modulus, Shear Modulus, and Poisson's Ratio for Glass and Glass-Ceramics by Resonance" provides a method for determining the rigidity of tile for engineering design purposes. Similar test protocols and established engineering formulae are available to determine the shear modulus of various tile substrates to assure that substrates have shear strength to resist shear stress that may be induced by adhesion of disparate materials with higher shear modulus characteristics, including the adhesive. Many studies regarding compatibility of adhesives and adhered materials have been conducted in the construction industry, most notably in brick masonry construction, where assessing compatibility between brick masonry and mortar compressive, shear strength, and flexural strength are important to proper performance of the composite brick masonry assembly [3].

While tile industry standards and basic engineering theory recognize that more deformable polymer modified cement adhesives can absorb and isolate differential movements common in high performance applications such as exterior building façades, there are many situations where a more flexible adhesive could be detrimental, or where shear strength of an adhesive may govern design.

It is a well known phenomenon that shear stress is uniformly distributed at the adhesive interface with more rigid adhesives, whereas shear stress is concentrated at the perimeter of the adhesive interface with more flexible adhesives. Engineering data also demonstrates that higher shear modulus adhesives exhibit a much more linear shear vs. strain behavior over a large range of stresses, and that lower modulus adhesives exhibit non-linear behavior, and consequently exhibit greater strains. So while highly flexible polymer-modified adhesives are better able to absorb differential movement between components of a composite tile assembly, their behavior is less mathematically predictable.

Leading manufacturers of re-dispersible polymers used in tile adhesive products have conducted numerous studies [4] regarding the capabilities of various polymer-modified tile adhesive formulations. It is generally known that deformable tile adhesives in compliance with EN 12002 / ISO 13007 Standard S1 Class contain approximately 3-5% polymer modification as a percentage of dry content weight, while S2 Class highly deformable tile adhesives require >9-10% polymer modification (figure 2). However, as shown in figure 3, there is a balance between linear, predictable performance of a moderately deformable adhesive, and non-linear performance of highly deformable adhesives. With very flexible polymer-modified cement adhesives, as polymer-modification increases, deformation may result in unrecoverable fatigue, whereby the adhesive's shear strength capabilities are diminished and can become more critical.

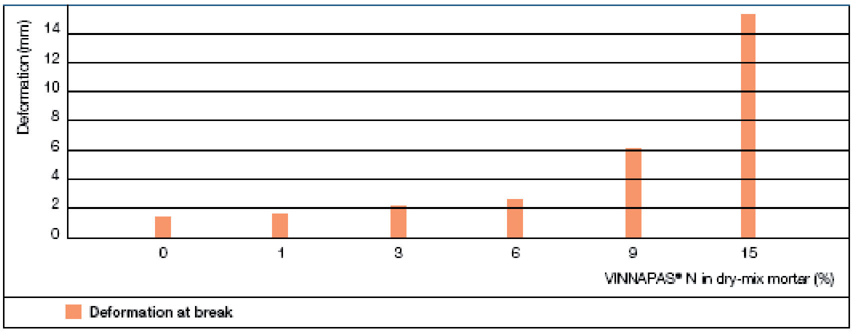

Figure 2. Effect of various percentages of polymer modification [4] on adhesive mortar deformation capabilities.

Therefore, deformation capability alone is not an indication of ultimate performance of a tile adhesive. As a result, testing and determination of shear strength and shear modulus characteristics, together with flexibility characteristics, can enable a more accurate assessment of a polymer-modified cement adhesive's performance under adverse conditions.

As in structural engineering of a building's structure, it is also helpful to know the ultimate strength characteristics of a polymer-modified cement adhesive itself, which differs from its shear strength when adhered to another material. This enables the designer to quantify the extent of shear stress the adhesive itself can sustain, and also whether that characteristic would govern the design under certain conditions.

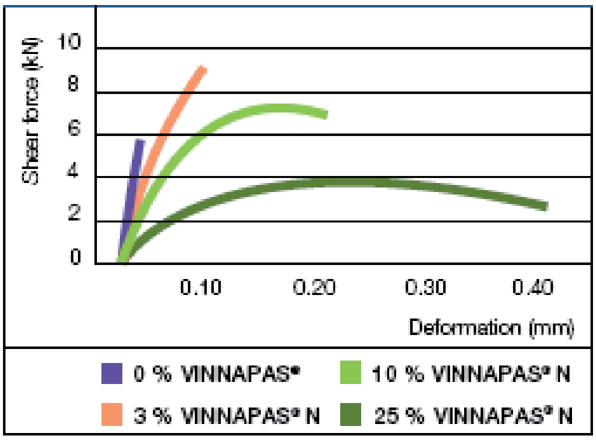

Figure 3. Graph of shear force vs. deformability [4]; shear stress capabilities are more predictable with moderately flexible polymer-modified cement adhesives.

- Fatigue cyclical loading / stressing of flexible, highly deformable adhesives may result in unrecoverable fatigue, whereby the adhesive's may yield to a plastic state, with accompanying reduction in shear strength capabilities. When subject to cyclic loading, these stresses and strains intensify and accumulate, resulting in potential internal cohesive failure or, failure at the adhesive interface.

- Plasticity and Elasticity When shear stress is induced on a flexible, highly deformable polymer-modified cement adhesive interface, the adhesive behaves initially in an elastic manner. Shear stress is accompanied by a proportional increase in deformation, and when the shear stress load is removed, the adhesive returns to its original shape / size. However, once the load exceeds a certain threshold (known as "yield strength"), the deformation increases more rapidly than in the adhesive material's elastic region, so when the shear stress load is removed, some amount of the deformation remains permanent and is unrecoverable. Plasticity describes the behavior of materials which undergo irreversible deformation without failure or damage. However, even highly deformable polymer-modified cement adhesives can not sustain any significant plastic behavior before internal fracture or shear failure. It is important to note, though, that predictable elastic deformation depends on time frame and loading speed, and that rapid loading, such as caused by a seismic event or thermal shock, can also result in sudden adhesion failure.

- Duration of loading duration of shear stress exerted on a polymer-modified cement adhesive is another factor which is of greater concern with a more flexible, deformable adhesive. Studies have shown that more rigid adhesives behave more favorably than flexible adhesives under sustained loading. Flexible adhesives exhibit greater initial creep.

- Durability of flexible polymers The issue of most concern regarding the performance of highly deformable polymer-modified cement adhesives is their long-term performance under actual temperature and moisture conditions. Recent research indicates that prolonged moisture exposure has a significant effect on deformation characteristics of certain formulations of polymer-modified cement adhesives when compared to laboratory samples of the same type and age. Bond strength degradation appears a less significant issue. [6]

When stored outside in normal in-service conditions over 180 days, transverse deformation characteristics were reduced from 15- 18% in some of the adhesive formulations, compared to 28 day cured laboratory samples. For the transverse deformation the highest result obtained under external conditions was 3.55 mm, which was 50% lower than the lowest value obtained from all adhesive formulations under laboratory storage conditions.

One school of thought on this issue is that flexibility of tile adhesives is more critical during the initial progress of construction of a building, as the majority of differential movement attributable to shrinkage and creep diminishes with age, and a more stable tile assembly and substrate requires less flexibility as a building ages. Nonetheless, studies indicate that shear strength remains an important and proven attribute of a polymer-modified cement adhesive, as does the need to qualify and quantify the long-term performance claims of certain deformable adhesive formulations.

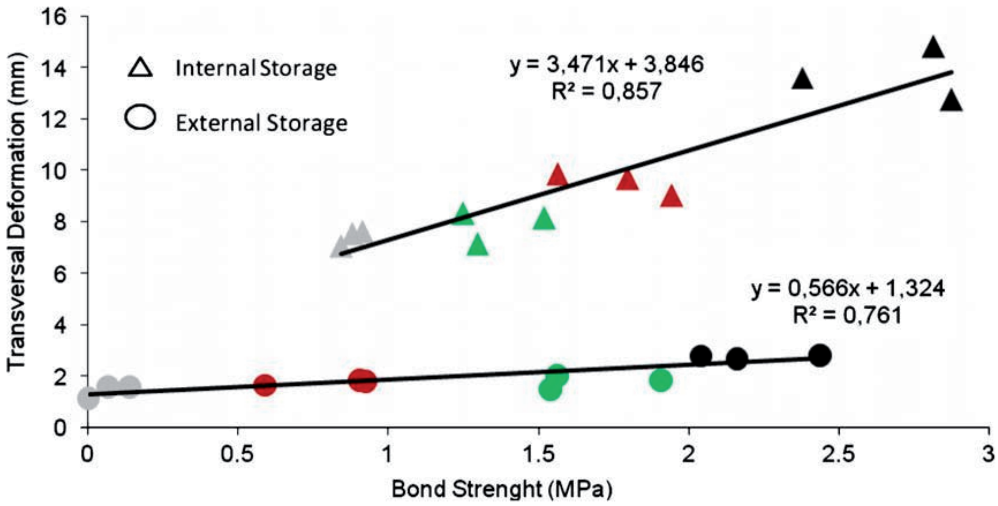

Figure 4. Graph comparing transverse deformation and bond strength of laboratory and exterior in-service samples at 180 day age [6]; note significant reduction in deformation of exterior samples.

6. CONCLUSION

While the new generation of flexible, deformable polymer-modified cement adhesive products is generally a positive development towards more successful direct-adhered tile and stone applications, further study and testing remain a top priority. Of greatest importance is the need to develop more objective and accepted engineering criteria for the design and specification of these adhesives, such as modulus of elasticity, shear modulus and shear strength requirements. Similarly, International standards (ISO), American standards (ANSI) and European norms (EN) and for the tile industry should incorporate such engineering criteria so that architects and engineers can make more informed, scientific decisions that will inspire more confidence and success with this important technology.

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