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Time Dependent Extension and Failure Analysis of Structural Adhesive Assemblies Under Static Load Conditions

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Abstract: The objective of the current study is to characterize the long-term stability and efficacy of a structural adhesive assembly under static load. An apparatus was designed to be used in the Instron tensile test machine that would allow for real time modeling of the failure characteristics of an assembly utilizing a moisture- cure adhesive which was bonded to concrete. A regression model was developed that followed a linear − natural log function which was used to predict the expected life of the assembly. Evaluations at different curing times confirmed the structure was more robust with longer cure durations prior to loading. Finally, the results show that under the conditions the assembly was tested, there was only a small amount of inelastic creep and the regression models demonstrated the potential for a stable structure lasting several decades.

Keywords: *Moisture cure, Hybrid polymer, Adhesive, Static load, Life testing*

1. Introduction

A Most building structures will require multiple types of functional components that may be preassembled or added at the site. Some of these components may include ties, hooks, clips, or hangers that are attached to the wall, floor, or ceiling [1]. The traditional procedure to attach these components to the walls or ceilings of the structure is to drill and mount mechanical fasteners. However, bonded structural components using adhesives in place of mechanical fasteners are becoming more commonplace in the construction process [2]. A few industries that can potentially replace mechanical fasteners with adhesively bonded structural component assemblies are transportation, marine, energy, aerospace, building/construction, and electronic components, etc. [3].

Adhesive bonding of structural components has been accumulating popularity during the past few decades due to the advantages it offers over conventional mechanical fastening techniques [4]. More specifically, elastomeric adhesives are increasingly being used in favor of nails or anchor bolts to secure these structural elements because of environmental advantages and/or cost savings in time and labor [5]. Other significant benefits of using adhesives over conventional mechanical joining techniques are the elimination of drilling holes in concrete, less load concentration, and higher fatigue resistance/increased endurance limit [6]. Furthermore, adhesively bonded joints are gaining acceptance in applications where the weight of the structural materials is an important part of the product efficacy and/or cost base [7-9]. To maximize success in the bonding process, proper selection of the substrate/adhesive combination, surface preparation, selection of bonding assembly hardware, and variables that control bonding are the most important steps [10].

Despite all the potential advantages and positive experience over many years with structural loading using adhesively bonded assemblies, manufacturers continue to be resistant to accept the technology in primary load-bearing components. This hesitancy is fundamentally attributed to a lack of understanding of the assembly durability over time, load limits, and fatigue-resistance/failure-mode of the device related to long term efficacy of the adhesive bond [11]. Further, as it relates to this work, the vast majority of structural adhesive assembly testing data is based on endurance models which capitalize on epoxy, urethane, or acrylic curing/crosslinking chemistries [12]. Therefore, the lack of data surrounding moisture-cured adhesives initiated this research into bonding characteristics with a structural assembly to be used in the building construction industry.

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The adhesive formula used in this paper is made from a moisture-curable, high-solids, single component hybrid polymer that is characterized by excellent green strength, high elongation to break, and exceptional final adhesion properties.

A specific application gaining some traction using structural adhesives is in the area of hangers, braces, couplings, and struts for electrical utilities, conduit, cables, switchgear, busbars, and boxes. Historically, these types of electrical utility components have been stabilized by drilling into the substrate and utilizing anchor bolts [13]. Some mounting methods include the addition of an adhesive into the drilled hole to provide additional stability to the anchor [14, 15]. However, cumulative evidence on the negative health effects of inhaled airborne crystalline silica has resulted in a fresh look at structural adhesives as an appealing alternative to drilling into concrete [16]. Likewise, some structural adhesives have even been successfully evaluated in seismically active zones because of their high green strength and vibration dampening characteristics. Under seismic duress, metal and other rigid components can suffer degradation and weakening due to fatigue. Advantages of adhesively bonded structural components are their ability to dampen vibration frequency waves, resist failure due to fatigue, and a general ability to maintain strength when subjected to cyclic factors [17].

Modes of failure over time due to inelastic deformation are critical to understanding long term static loading dynamics for structural components that rely on adhesive bonding systems [18, 19]. A structure may prematurely fail from inelastic deformation due to several manageable reasons related to the assembly of the system. Therefore, stress life and strength prediction analysis along with substrate preparation criteria are required for these structures; especially for the instance of fail-safe or damage tolerant designs [20-25]. However, accurate prediction of stress life can be a challenge due to the complicated nature of failure mechanisms, geometry of bonded joints, and complex material behavior under static load. Understanding the mechanism of elastic deformation and the onset of inelastic creep is also important to develop a working model of failure.

There are several methods suitable to test and characterize a structural adhesive as part of an electrical hanger assembly [26]. The evaluation scheme chosen in this work was to assess the adhesive properties with a specific adherent as part of a systematic study of the total assembly [27]. This manner of approach focuses on the interactions of the assembly together with the adhesive to provide a more general but synergistic indication of overall structure dynamics. Specific testing in this study imposed a tensile load upon the adherent-adhesive-substrate joint. This method of testing will increase understanding about the ultimate load supported by the assembly, endurance limits at various load values, and creep of the adhesive bond throughout the life cycle. Further studies should include the structural influence of different adherents using this procedure while continuing to keep the adhesive chemistry constant.

The objective of this paper is to first report on a dynamic time/static-load test to model and demonstrate the ultimate fatigue and failure of elastomeric adhesives in structural applications. Second, to report on a methodology using an elastomeric adhesive conceived to act as a replacement for mechanical fasteners in electrical hanger applications. Third, to determine the minimum curing time required for the structural adhesive to tolerate a load. Finally, this study reports on the long-term efficacy of a structural adhesive designed to support and reinforce commercial utility hardware with an electrical hanger assembly designed for use in the building construction industries.

2. Experimental

2.1. Materials

The adhesive used in this study, identified as Seal Bond^{TM} SB-EHA, is a single component, fast skinning, and high elongation-to-break moisture cured hybrid polymer that is a component of a comprehensive electrical hanger system sold by Seal Bond^{TM} Inc. under the name of Safe Anchor^{TM} [28]. The total length of time required for complete cure of this moisture cured hybrid polymer is ~14 days at 21 degrees centigrade and 50% relative humidity. The skin over time of this polymer is ~8 minutes. These types of polymeric chemistries have been shown to possess long term durability in both elastomeric and adhesive

properties in critical construction applications [29]. The structural makeup of the moisture-cured hybrid material used in this study falls under the heading of an alpha omega telechelic silyl-terminated polymer with a generalized formula resembling: $(RO)x\text{-}Si\text{-}(CH_2)y\text{-}(R')z\text{-}$

(CH$_2$)y-Si-(OR)x [30]. Where R can be a methyl, ethyl or acetyl group and R' is a repeat unit that may consist of a polyacrylate, polyether, polyurethane, polyester, or polyurea functionality. X and Y are integers of 1, 2 or 3. In the presence of moisture, -Si(OR)x hydrolyzes and becomes -Si(OH)x [31]. The telechelic nature of the polymer will further allow two −(Si-OH) functionalities to reactively condense and form (Si-O-Si) in the presence of a catalyst [32].

The anchor used in this study is the integral part of the Seal Bond$^{\text{TM}}$ Safe Anchor$^{\text{TM}}$ system and shown in Fig. 1 It is die-cast of a Zinc-alloy, and the geometry of the base was designed for use with structural adhesives. It has an outside diameter of 7.62 cm which results in a base contact area of 45.6 cm^2. Due to the holes in the hanger pad, the entire surface area of adhesive contact on the anchor is significantly higher but since the locus of failure occurs in the cross-sectional area between the adherent and the substrate, accurate knowledge of the surface area of the anchor is not necessary for the purposes of this work.

Cured concrete was used as a representative substrate for the attachment and testing of the Safe Anchor$^{\text{TM}}$ system. Concrete test blocks were obtained in a size of 25.4 cm x 30.5 cm x 5.1 cm (nominal). The test blocks were then cut into four pieces to fit the test apparatus. The whole and cut concrete blocks are shown in Fig. 2 below. The cast concrete surface from the supplier was unmodified from the mold and was not finished in any way. For further details about the concrete tested, see Appendix A.


6.35 mm - 20 UNC female thread

9.53 mm - 16 UNC female thread

Figure 1. Safe Anchor$^{\text{TM}}$ system showing both the 6.35 mm and 9.53 mm threaded options.

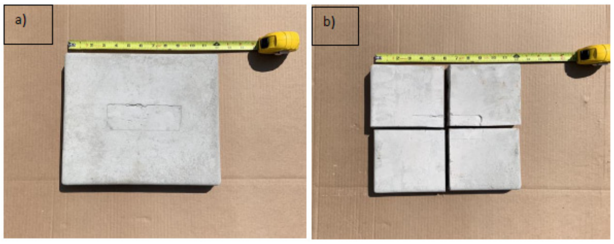

Figure 2. a) Whole uncut 25.4 cm x 30.5 cm x 5.1 cm thick concrete block and b) four 12.7 cm x 15.24 cm x 5.1 cm thick parts of the concrete block after cutting to fit test apparatus (all dimensions are approximate).

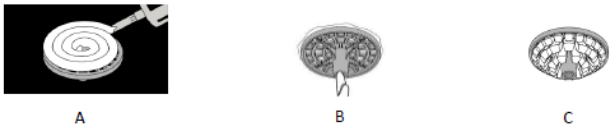

Figure 3. Mounting procedure for application of adhesive to anchor and attachment to concrete ceiling. A – application of adhesive to anchor; B – anchor pushed onto surface; C – correct appearance of extruded adhesive through holes of anchor.

2.2. Experimental Setup

T Surface preparation prior to testing of the concrete block consisted of brushing the surface lightly with a nylon bristle brush to remove any grit, dust, or loose material. In all tests, the adhesive was applied to the anchor in a spiral pattern and mounted on the concrete surface as shown in Fig. 3. The anchor was pushed perpendicularly onto the concrete surface without any twisting or side-to-side movement until flush, fully seated, and the adhesive extruded through the openings of the anchor. The assembly was then allowed to cure for a specific time period for each individual test.

The testing process chosen to study the endurance and failure limits of the Safe Anchor$^{\text{TM}}$ system in the tensile mode required creation of a test apparatus for rigidly retaining the concrete surface in a horizontal position. The custom-engineered apparatus concept was designed to be compatible with an Instron machine model 3345. Design constraints for the test apparatus required that it must be able to hold the concrete block rigidly by the edges while allowing for increasing the load perpendicular to the concrete surface to both a constant load and until failure of the bond or any of the component parts. The test apparatus consisted of a welded steel assembly sized

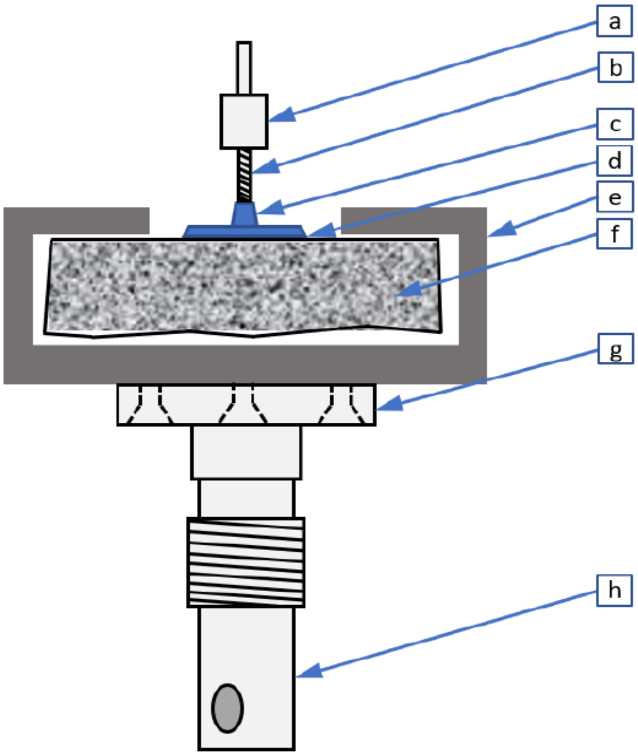

Figure 4. Test apparatus for use on Instron machine: a) threaded fitting for upper tensile-jaw attachment, b) threaded rod, c) Seal Bond^{TM} Safe Anchor^{TM}, d) adhesive, e) welded steel assembly for retaining concrete block, f) concrete block, g) flanged fitting to match Instron machine mounting geometry, h) connection point to the Instron machine.

to accommodate the thickness of the concrete block while providing an opening through which the anchor could be exposed for load testing. The welded steel assembly is rigidly attached to a flanged fitting that matches the Instron machine's mounting geometry, shown in Fig. 4. The welded steel assembly allows the concrete block to be inserted from the side by the operator in order for test preparation to be accomplished in a short amount of time. Ease of assembly is important because consistent cure-times are critical for statistical reproducibility.

The concrete block surface was prepared as noted above; the hanger base was prepared by wiping with isopropyl alcohol and allowed to air-dry. Adhesive was applied to all areas of the base in a spiral pattern with a thickness of approximately 7.62 mm as shown in Fig. 3A. The hanger base was adhered to the center of the concrete block using the adhesive and properly seated by using the method described in Fig. 3B. After the predetermined cure-time, a threaded rod of ~7.5 cm in length was screwed into the threaded portion of the hanger pad. An attachment fitting designed for the tensile test machine's gripping jaws was then threaded on to the other end. The threaded rod was able to freely rotate as the tensile load was applied. For purposes of this paper, the concrete block was placed with the hanger pad up for simplicity. When the test apparatus was completely assembled and installed into the Instron, the loading on the system was initiated.

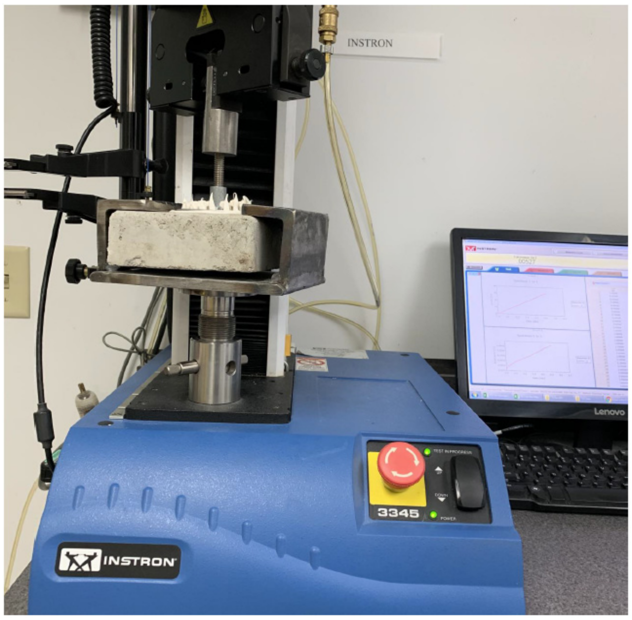

Figure 5. Photograph of the test apparatus with the Seal Bond^{TM} Safe Anchor^{TM} system installed and ready for test.

Vertical loading perpendicular to the concrete surface was intended to simulate the weight of building structure utility components on the hanger system which is the most common application and mode of use. The test apparatus is installed in the Instron machine as shown in Fig. 5. The test apparatus is flexible enough to be positioned either with the hanger pad pulled from the top or the bottom. For the purposes of this study, the orientation of concrete on top or bottom was considered unimportant because the effect of gravity upon the hanger pad and fastener is negligible. The Instron machine records and plots the load in pounds-force and displacement against elapsed time at a designated static load. Depending upon the specific test, the loading is maintained for a prescribed time or until failure. Initial movement and seating of the concrete block against the welded test apparatus are disregarded and excluded from the data.

The cure time of the adhesive was varied for the testing because as the adhesive cures, it is capable of handling increasingly higher loads. While the adhesive is not fully cured, the cure times chosen were intended to demonstrate the ability of the assembly to handle loads typical in many applications.

Using the apparatus shown in Fig. 5, the anchor was applied to the concrete following the method shown in Fig. 3. The adhesive was then allowed to cure for the test times; 1, 4, and 6 hours. In the first series of tests, each cured sample was placed in the Instron apparatus and secured with the upper clamp of the machine. The Instron was programmed to exert a load on the block to a set force; 222.41, 444.82, 667.23 Newtons (N), for a 1 hour duration. The force was maintained for the hour or until failure, whichever occurred first. The extension of machine was monitored over the course of the test. Data points were measured every 0.1 seconds.

In the second series of tests, samples were prepared following the same procedure. The samples were allowed to cure for 1, 4, and 6 hours. These samples were placed in the Instron and secured. The program was then set to pull the anchor to 111.21 N load to seat the block in the apparatus. The load was then increased on the sample at a rate of 133.45 N / min until failure. The extension was measured every 0.1 seconds.

3. Results and Discussion

3.1. Data Analysis

When a load is initially placed on the assembly, the adhesive should retain its elastic character. As the load is progressively increased, the adhesive will eventually experience stress beyond its yield point. Once the adhesive reaches the limit of elastic deformation, the stresses will equalize across the hanger pad boundary. With increasing load, a limit will be found where the adhesive will not be able to sustain the force. This is the point where the adhesive ruptures and fails [33]. The typical failure mode of all samples was a thin film adhesive failure.

The loads chosen were intended to represent a worst-case scenario in time dependent stress vs performance requirements for the assembly design. In actual structural applications, manufacturers will recommend a safety factor on the hanger assembly that is no more than 33% of the highest stresses that it can withstand.

The plot of the extension versus time, shown in Fig. 6, appeared to be a logarithmic relationship. A plot of hanger pad extension versus natural log time is shown in Fig. 7 for a 444.82 N load. A linear − natural logarithmic regression was done for the cure times of 1, 4, and 6 hrs. The regression equations with correlation coefficients at a 444.82 N static load and different cure times are shown below:

1 hour cure − $Y = 0.0055X + 0.0103$ $R^2 = 0.9968$ (1)

4 hours cure − $Y = 0.0017X + 0.0024$ $R^2 = 0.9736$ (2)

6 hours cure − $Y = 0.0083X + 0.00009$ $R^2 = 0.9926$ (3)

In this linear-natural logarithm model, the value of Y is the overall extension of the system which will increase by the slope of the line with each one unit increase of the value of X, which is the ln of time in seconds.

To model the ultimate failure of the assembly under static load, information was needed on the extension of the adhesive at the point of adhesive breakdown. Experiments were done to model the extension at the point of failure using different cure times and shown in Fig. 8. A linear releationship was obtained which represents the increasing strength of the bond and a more robust adhesive network with cure time. The slope of this line is expected to approach horizontal as the cure time (~14 days) approaches the fullcure strength of the adhesive. The actual measured extensions at failure with standard deviations are shown in Table 1 for each cure time.

Data points were only taken when the adhesive began to bear the full load applied for each test. When the full load is applied, there is an initial elastic deformation of the adhesive. When elastic deformation is complete, the total weight from the load will begin to redistribute across the complete adhesive boundary; which occurred within seconds in each test. Once the stress was disseminated evenly across the adhesive boundary, a small amount of creep deformation was observed in each test. While a minor amount of creep deformation was observed within 60 minutes of time, there was no evidence of any failure due to the onset of stress rupture in the adhesive. Furthermore, the heaviest loads placed on the assembly were approximately 4 times that which would be expected in the actual on-site application as an attempt to model worst-case scenarios.

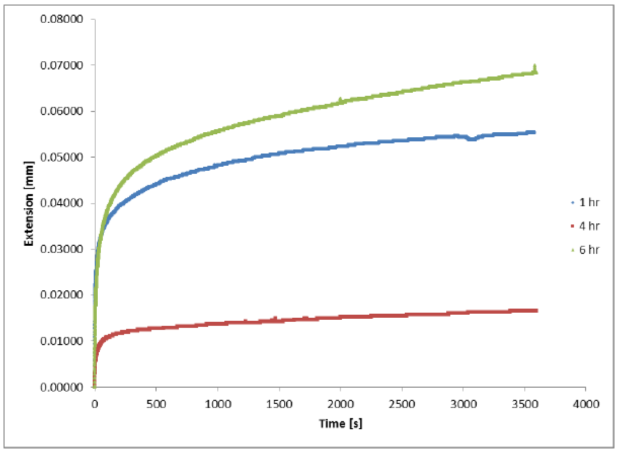

Figure 6. Extension vs Time at 444.82 N static load at 1, 4, and 6 hour cure times.

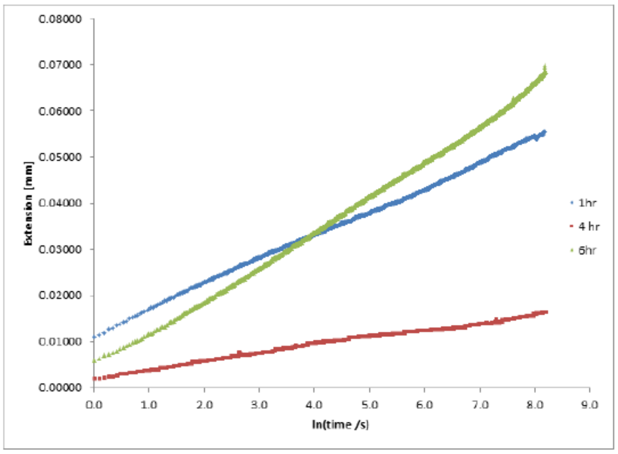

Figure 7. Extension versus natural log of time for 444.82 N static load at 1, 4, and 6 hour cure times.

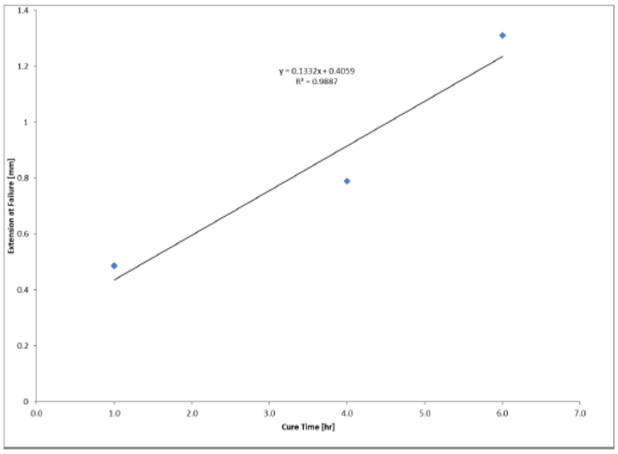

Figure 8. Regression plot of extension at the point of failure vs cure time of the adhesive.

Table 1. The extension to failure of the adhesive at different cure times

Cure Time (hrs)	Extension to Failure (mm)	Std. Dev. (mm)
1	0.487	0.077
4	0.939	0.074
6	1.311	0.087

Table 2. Calculated time for adhesive failure at different cure times

Cure Time (hrs)	1			4			6		
Load (N)	222.41	444.82	667.23	222.41	444.82	667.23	222.41	444.82	667.23
Time to Failure (Years)	$1.3\text{x}10^{33}$	$1.4\text{x}10^{30}$	Failure	∞	∞	$5.7\text{x}10^{43}$	∞	∞	∞

The extension to failure data in Table 1 were used along with the linear - natural logarithmic regression equations shown previously to calculate the expected duration (in years) of the adhesive bond for a static load. These numbers were calculated from each different regression equation generated from data obtained at different static loads and shown in Table 2. Only the sample at 1 hour of cure and 667.23 N load failed due to adhesive rupture. Assuming that inelastic creep is the only process at work in the other test assemblies, the magnitude of these numbers strongly implies that the odds of a failure occurring within several decades is remote. Only the test using the lowest cure time and highest load produced any evidence of adhesive rupture following low amounts of creep. Assembly failure is then directly proportional to load and inversely proportional to cure time.

4. Conclusion

A procedure has been developed to model the life expectancy of a moisture cured structural adhesive under static load. A linear − natural logarithmic relationship has been identified with cure time and extension at failure that has a correlation coefficient of 0.9887. Catastrophic failure has been modeled using extension to failure numbers derived from different adhesive cure times. All failure mechanisms were thin film adhesive failures.

While every test at different cure rates showed a slight indication of inelastic creep, only one sample (lowest cure time and highest static load) ruptured prior to 60 minutes. The probability of catastrophic failure increases as the cure time shortens and the static load increases. A safeguard to guarantee the long term viability of the assembly would be to use a cure time of 4 hours or greater, and a recommended weight that is at most 33% of the highest successful loads tested in this study.

Declaration of Interest

All authors of this article are employees of Seal Bond Inc., a manufacturer of adhesives, sealants, and coatings, who also financially supported this work.

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