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Durability and accelerated ageing testing of CFRP repair systems

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ABSTRACT

Epoxy bonded CFRP is a commonly used method of strengthening or repairing concrete structures; however, the long term performance of the epoxy bonded materials is not clearly defined. Accelerated ageing of CFRP specimens has long been a contentious issue since the environmental conditions used during the ageing process are not always present in the field. This paper presents a conceptual model for behavior of accelerated ageing, actual test results in water immersion and observed strength reductions. A three point bend test is presented to evaluate the strength degradation due to accelerated and normal ageing of bonded CFRP reinforcement. Critical parameters are found to be inherent epoxy properties and the water content at the CFRP/concrete interface. The three point bend test has a lower coefficient of variation than the direct tension test. A methodology is presented for conducting accelerated ageing tests for two field conditions: immersion in water and in air. The accelerated ageing process allows an engineer to prequalify CFRP bonded strengthening systems and to establish a strength reduction factor for a given CFRP system.

1 INTRODUCTION

Accelerated ageing to evaluate durability of repair systems has long been a goal of engineers attempting to determine the suitability of a new material for structural engineering applications. In an ideal world the mechanics of ageing would be well known and mathematical models available, and ageing behavior could be accelerated by adjusting the critical parameters within the mathematical model. This goal has been achieved for some material behavior. For example, the nuclear industry has mathematical models for steel embrittlement, for concrete carbonation, and for sulfate attack (ACI 365 2000). In each of these cases both a physical material model and a mathematical model for deterioration exist. When the mechanism is not well known, materials are exposed to variations of their service environment, degradation rates recorded, and strength reduction factors extrapolated based on the experimental results. Interpolation of the test data becomes the basis for service life and strength reduction predictions.

The goal of accelerated ageing testing is to reduce the time required to characterize behavior. Accelerated ageing is typically achieved by increasing the temperature or the concentration of ageing agents to accelerate chemical processes. Engineers are particularly careful to limit the temperature and concentration to avoid initiation of reactions that would not occur in normal operating environments. For example, elevated temperatures are at least 15C below the glass transition temperature, T_g, to prevent chemical changes in the epoxy. Without a sound understanding of the adhesive bonding, it is not possible to know the critical limit states in advance. Without this knowledge, it is not known if a limit state is exceeded in the accelerated ageing process.

This paper addresses the mechanics of water on adhesively bonded CFRP reinforcement. It begins with a discussion of an ideal adhesive bond, followed by a conceptual model and an examination of the nature of adhesive bonding, then progresses to experimental testing and finally addresses determination of strength reduction factors for CFRP systems. Factors leading to confusion in the interpretation of durability test results are identified.

An ideal adhesive bond has the following characteristics: the adhesive is stronger than the adherand throughout the life of the structure and minor flaws in the adhesive are not fatal to the system. In practice, this means that the concrete surface is roughened and dry. Dry in most cases means that no condensation forms on a plastic sheet taped to the surface (Gaul 1984). An adhesive with strength that is much higher than the adherand means that small flaws in the adhesive bond surface are not critical to the overall performance and failure occurs in the concrete substrate. The “dry” requirement reflects that water, and specifically water content at the adhesive interface, is known to be an important factor in the durability of adhesive connections (Mays 1992). The interface between the adhesive and the adherand is generally considered critical for durability. While numerous studies address fracture in the adhesive, failure at the interface is often just as brittle and less predictable than fracture through the adhesive (Mays 1992).

2 ADHESIVELY BONDED CFRP BEHAVIOR

The micro-mechanics of adhesive bonding between CFRP and concrete are not well defined. Two factors are generally recognized as contributing to the bond: mechanical interlock and surface bonding, which includes hydrogen bonding. The following discussion postulates how these two behaviors interact to explain water effects on durability. The discussion further assumes that an epoxy adhesive is used to bond either fabric or laminate CFRP materials to the concrete. Lastly, the paper examines only water content and temperature as variables in accelerated ageing. Even with these limitations, the conceptual model of adhesive behavior assists in understanding accelerated ageing limitations and provides a basis for defining material properties need to improve durability.

2.1 *Mechanical Interlock*

Mechanical interlock occurs when the liquid adhesive penetrates the concrete surface of the adherand and then solidifies to create the interlock, Fig. 1. A highly viscous epoxy will not flow readily on and into the concrete surface. The surface energy of the epoxy is overcome by mechanical energy expended in rolling the resin onto the surface. Locations a and b in Fig. 1b shows a fully interlocked adhesive bonding. Fig. 1c shows potential flaws in the coating application at the same locations. Fig. 1 suggests why tensile testing is more sensitive to adhesive bonding than shear testing. Flaws at locations a and b in Fig. 1c will have less effect on a shear test and a larger effect on the tensile test. Thus, a larger coefficient of variation would be anticipated from a tension test than a shear test.

Accelerated ageing uses elevated temperature to accelerate water absorption. Elevated temperature reduces the elastic modulus of the cured epoxy. This in turn allows the adhesive to separate from the adherand sooner than control conditions. The adhesive with lowered stiffness will exhibit accelerated creep compared to the field application. Thus, testing must return the specimen to field or room temperature to assure interpretation of the results.

Water absorbed into the adhesive plasticizes the epoxy. This leads to a lower T_g, a lower modulus of elasticity, and an increase in the creep rate. All of these factors accelerate the mechanical separation of the adhesive. Water uptake is a thermodynamic property that is dependent on the sensitivity of the material to absorption, the temperature, and the available water. Submerging the specimen in water provides the highest vapor pressure and maximum absorption. Elevated temperature can further accelerate the absorption rate.

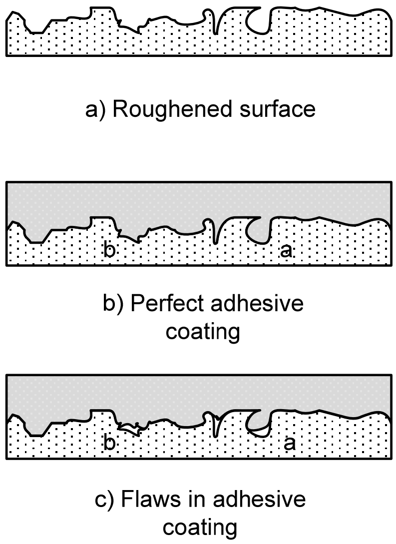


Figure 1. Adhesive surface coating

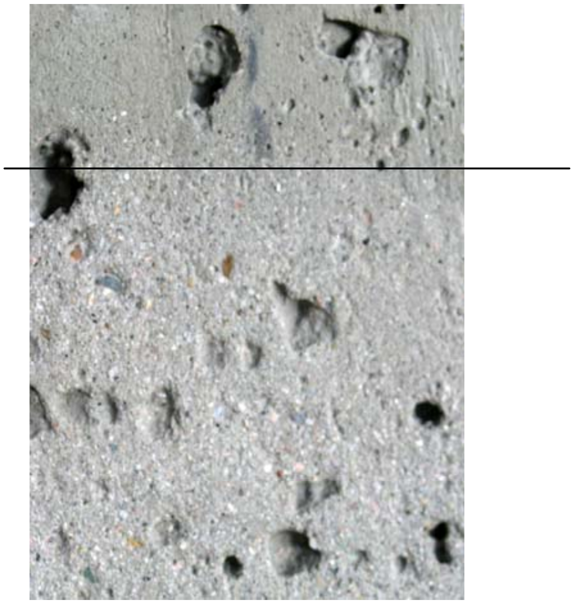


Figure 2. Prepared Concrete Surface

Assessing water content in the epoxy is dependent on the ability of the water to migrate through the adhesive. One critical parameter in water migration is the difference between a 100% relative humidity condition and a saturated wet condition. There is a three orders of magnitude increase in water content between a 100% relative humidity environment and a submerged condition. Vapor pressure in air is much lower than the saturated exposure condition, so submerged tests may not represent the field application. Thus, a submerged exposure test may unduly compromise the behavior of an epoxy subjected to an air only application. Conversely, if water can accumulate on the bond line of the soffit of a structure, e.g., bridge or parking structure, then the submerged condition may be the correct ageing environment.

The Arrhenius equation, commonly used to predict ageing, provides a method of mathematically modeling absorption. If absorption is the only critical parameter, the Arrhenius equation can correlate time and degradation. The equation is not sensitive to phase changes as may occur between exposure to air or immersion. Were mechanical bonding the only mechanism in play, a deterministic model of this behavior could be developed.

2.2 *Surface Bonding*

Surface bonding consists of the chemical interaction between the epoxy and the concrete. Hydrogen bonding is the affinity of hydrogen atoms to align with other atoms to create a weak bond and is a major contributor to surface bonding. In the simplest example, hydrogen bonds are what hold water molecules as a liquid at room temperature and allow ice to form and stick to other materials (Ashby 1980). Hydrogen bonds are one to two orders of magnitude weaker than other bonds but become significant when large areas are exposed (Mays 1992).

The ability of an adhesive to generate hydrogen bonding is dependent on its chemical composition. For example, an epoxy with a large number of hydroxyl ends may have a different affinity for hydrogen bonding than an epoxy with a smaller number of free hydroxyl ends.

Without knowledge of the exact epoxy formulation, curing, and affinity for water, isolation of these effects is difficult.

Consider the effects of hydrogen bonding between an epoxy and concrete. In a "dry" concrete surface, hydrogen bonding could occur between the epoxy and the calcium-silica-hydrate (CSH) formed from curing cement. Addition of free water molecules could either displace the CSH-hydrogen bonds leading to a large loss of bond strength or create a small separation in the bond area leading to a small loss of strength. Without a valid chemical model, prediction of this behavior is not possible and testing becomes the default method to characterize the bond. Structural engineers need this information from the polymer chemists and scientists.

The Arrhenius equation can account for the rate of water moving through the materials but it may not account for chemical interaction in hydrogen bonding. The equation may correlate test data but may not effectively identify quantum changes in behavior.

2.3 *Bond Interactions*

In the above conceptual model, moisture affects both the epoxy resin properties and the surface bonding. Thus, exposure to water (liquid or vapor) as a sole accelerated ageing factor is insufficient to differentiate between the contributions of each action on the overall bond performance. At present, there is no reliable method to separate the two actions.

An adhesive exposed to a water bath at elevated temperature may lead to one of two results. Either the adhesive responds with a small strength loss or a large strength loss, "small" and "large" being relative at this point. If an adhesive system has a small strength loss when submerged in a water bath, it may be judged to be suitable for field application. If it has a large strength loss, it may not be suitable for applications where it will be exposed continuously to water, but it may still be suitable for "air" only applications.

The magnitude of "loss" is further complicated by changes in failure mode. If the control specimen exhibits a bond failure, then all subsequent losses are due to bond degradation. If the control specimen initially exhibits a concrete substrate failure, then the losses are due to changes in bond characteristics affecting the stress transfer to the concrete and a change in failure mode to bond failure. The reported losses include all bonding effects plus the effect of the concrete strength in the control specimen. This asymmetric condition is not usually addressed in research reports. In this later case, it is essential that the concrete strength used for evaluation of the epoxy/CFRP system is comparable to that used in the field. Failure to address the concrete strength can lead to over or under-estimation of the total loss.

Lastly, an examination of the concrete surface prepared for application of a bonded CFRP system indicates how surface preparation influences both mechanical and hydrogen bonding performance. Figure 2 is a close-up photo of a specimen surface. The lower part of Fig 2 is fully sandblasted while the upper part has minimal sandblasting. The total surface area of the lower part of the picture has increased improving mechanical adhesion and surface bonding. The fine sandblasting may be effective in increasing both mechanical and surface bonding; however, the larger micro-surface area improves performance. When examined from a bond and mechanical anchorage viewpoint, full sandblasting may be as effective as macro scale surface preparation such as bush hammering.

3 ACCELERATED AGEING TEST PROGRAM

Two commercially available adhesives were used to bond a CFRP fabric to a 200 mm x 200 mm x 380 mm concrete block, Fig. 3. (Epoxy A is a Sika 2 part epoxy and fabric and Epoxy B is a multipart Huntsman adhesive and BASF fabric system.) A tension pull off sample is adhered to the end of the block and flexural strip is placed on the tension face of the block thus both interface shear and direct tension results are available from a single specimen.

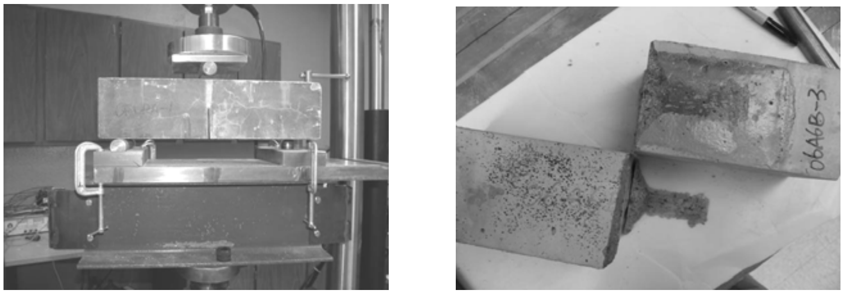
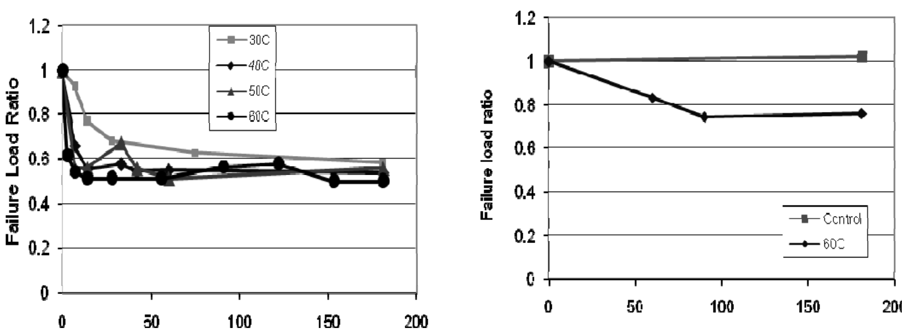


Figure 3. Flexure Test and Specimen Bond Failure

Test results indicate the difficulty of assessing the accelerated ageing response. Two adhesive systems are subjected to identical exposures. Commercial Epoxy A, Fig. 4a, indicates a strength loss of 40 to 50% after an exposure of 200 days for four different temperature domains. Commercial Epoxy B, Fig. 4b, shows a strength loss of less than 25% in the same time frame at 60C. In addition Fig. 4b contains the data from the control specimen, which gained approximately 5 percent in the same time frame.



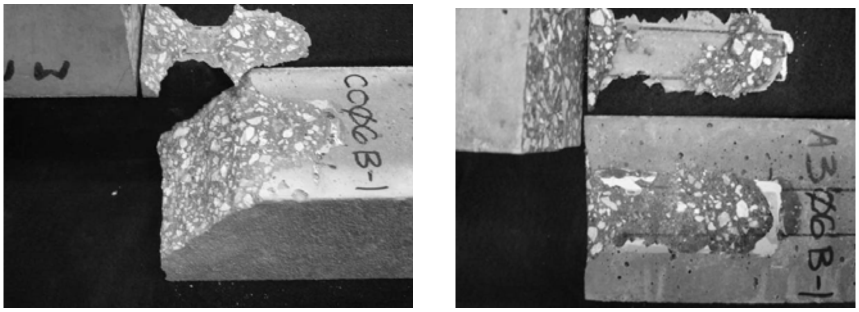
Exposure time(days)

a) Epoxy A Epoxy B

Figure 4. Strength Comparison of Two Commercial Epoxy Adhesives Subjected to Submerged Exposure

Complicating the interpretation of the test results is that the concrete in Fig. 4a has a strength of 72 MPa while the specimen in Fig. 4b has a strength of 42 MPa. Thus, Epoxy A has a higher “starting” capacity than Epoxy B and therefore, indicates a greater “loss.” In bond critical applications, the losses indicated in Fig. 4 are correct for both cases. Differences in failure modes are shown in Fig. 5. Figure 5a is the control specimen with a substrate failure. Figure 5b has a partial bond failure.

Examining these two results leads to several possible conclusions. An engineer could first conclude that Commercial Epoxy A is unsuitable for a wet application. Alternatively, a durability strength reduction factor of 0.5 may be selected and applied on all bond related calculations. Epoxy system B could be selected with a durability strength reduction of 0.75. In neither case is there an immediately recognizable method to correct for differences in concrete strength. Without knowledge of the effect of water on mechanical interlock and surface bonding determination of a durability strength reduction factor can only be established experimentally.



a) Substrate shear/interfacial failure b) Adhesive/interfacial failure
Figure 5. Failure Mode Comparison

For example, Epoxy A was retested in air at 100% relative humidity and 42 MPa concrete to evaluate suitability for inclusion in a project with a "dry" environment. Epoxy A exposed to water submersion at 30 C has results shown in Fig. 4a but when exposed to moist air responds similar to Fig. 4b. The available water resulting from full submersion affected the bond strength differently than the available water content in air.

In the examples given above, the test data suggest Epoxy A is not suitable for a wet environment. Thus, the three point bend test, with the appropriate concrete strength, is capable of identifying materials that are incompatible in submerged environments. Testing in a wet-room or other moisture controlled environment is needed to validate performance in air.

4 CONCLUSIONS

A science based understanding of bond behavior and a range of accelerated ageing tests are needed to qualify a CFRP/epoxy system. If the repair zone of the structure allows water to accumulate on the concrete/adhesive interface, then a submerged accelerated ageing test is needed to qualify the system. If the repair is in moist air, the water submersion may be too severe; however, a submerged test will identify adhesive systems that are at risk of rapid deterioration in water.

Most importantly, CFRP system suppliers should provide the strength loss information for specimens subjected to both high humidity and water immersion for a range of concrete strength. Such data would be invaluable to the engineer selecting a CFRP/epoxy system.

5 ACKNOWLEDGEMENTS

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