Kent A. Harries

Ph.D., P.Eng.

February 2, 2005

Danny Warren
Warren Environmental Inc.
PO Box 1206
Carver MA 02366

RE: Structural Testing of Warren Environmental Products

Attached are project summaries of three related projects for which I served as Principal Investigator. All three projects were conducted at the University of South Carolina where I was an Assistant Professor of Structural Engineering. I have since moved to the University of Pittsburgh.

I have conducted a number of investigations of the use of spray layed-up epoxy materials for the repair of concrete infrastructure. These investigations have focused primarily on the enhancement of structural properties afforded by the epoxy material and a composite composed of the epoxy and chopped E-glass fibers. In all projects, the performance of the Warren epoxy systems has been excellent.

There is certainly no question as to the efficiency of epoxy in sealing concrete tunnels and/or pipes. I have seen the product applied in wet environments varying from "damp" to puddled water. Although the bond quality is adversely affected by the presence of water, bond strength, nonetheless, surpassed the capacity of the concrete substrate. Bond quality under dry conditions is exceptional. As with any bonded product, however, substrate preparation is the key to sound performance. Properly followed specifications and thorough onsite quality control and material sampling/testing are critical to a successful installation.

Material testing of the epoxy product from 1/8 inch castings indicates exceptional material properties for this type of material which is largely the reason that I am interested in pursuing this material as a medium for structural repair.

Best Regards,

Kent A. Harries, Ph.D., P.Eng.

voice: 412.327.5183 • fax: 412.624.0135 • kharries@engr.pitt.edu

PROJECT SUMMARY

Sprayed Fiber Reinforced Polymer (SFRP) Materials for Concrete Rehabilitation

The objective of this research program was to introduce and evaluate the use of spray layed-up fiber reinforced polymer (SFRP) composite materials to the field of structural rehabilitation. This rehabilitation technique is similar to that used in a spray lay-up plastic molding process. Such a lay-up procedure is inexpensive, versatile, rapid, easy to apply, and requires relatively little preparation of the surface to be repaired. The application of SFRP materials to structural rehabilitation had never been quantified and only attempted on a very limited and specialized basis. This investigation identified parameters affecting the structural properties of SFRP rehabilitation measures, including fiber loading and coating thickness, and identified potential real-world applications for this technology.

In order to evaluate the application of SFRPs and to investigate their behavior when applied to concrete, an investigation to characterize the structural properties of SFRPs was carried out. *In situ* material characterization of the flexural strength (ASTM C78), flexural modulus (ASTM C78) and toughness (ASTM C1018) enhancement provided by SFRPs was assessed. This investigation emphasized measures of the toughness of the SFRP and the durability of the SFRP-to-substrate bond. Both were felt to be often-overlooked parameters that are exceptionally important in rehabilitation applications. This investigation also assessed the practicality of the rehabilitation material and technique.

In this study, the SFRP was made up of a chopped E-glass fiber embedded in the Warren Environmental T301 epoxy system. A matrix of 36 flexural beam specimens (ASTM C78 and C1018) having varying SFRP thickness (125, 250 and 500 mil) and fiber loading (0%, 5%, 10% and 15%) was tested.

The project report provides a brief background of SFRP and summarizes experimental results characterizing the strength, stiffness and toughness of the material. SFRP materials were observed to enhance the strength, toughness, and deformation capacities of plain concrete beams. In particular, SFRP was observed to fully rehabilitate deteriorated concrete beams. Factors affecting the quality of the final product are also discussed.

This initial investigation addressed many issues regarding the use of SFRPs for concrete rehabilitation. The following conclusions were made from this pilot study:

1. An optimum coating thickness near 250-mil will maximize the increase in load carrying capacity for specimens having epoxy only. The presence of chopped fiber, at the volume ratios provided (less than 15%), had no significant additional effect on the load capacity of the specimens. However it is noted that, in general, increasing the fiber load does increase the load carrying capacity slightly.
2. Concrete deformation capacity was increased by the presence of epoxy. The additional presence of fiber, at the volume ratios provided, had little additional effect.
3. Significant post-peak displacement capacity was obtained with a thicker epoxy coating. The addition of fibers in the SFRP material resulted in a significantly greater increase in post-peak displacement capacity, and thus energy-absorption capacity.
4. For the parameters investigated, the flexural stiffness of the specimens was not significantly affected by the presence of the epoxy or SFRP.
5. Like all FRP materials, SFRP has an apparent reduced *in situ* strength compared to tensile coupon tests.
6. Unlike conventional FRP applications, SFRP is well suited to direct application to moderately deteriorated concrete surfaces.
7. SFRP provides good mechanical bond to concrete surfaces with minimal preparation.
8. The following factors have been observed to affect the quality of the SFRP product: (a) skill of the person applying the SFRP (this may affect coating thickness and fiber volume); (b) epoxy temperature (c) application orientation (vertical or overhead); and, (d) type of fiber (this particularly affects wet-out properties).

The T301 epoxy material used in this study appeared to enhance the plain concrete flexural properties sufficiently for structural rehabilitation. The presence of fiber at the volume ratios provided had little effect on the flexural behavior. It is proposed that the fiber ratio needs to be increased for the fiber to have a significant affect. Practical issues of workability, however, make such an increase difficult to obtain. This trade-off needs to be addressed with additional research.

The objective of this pilot study was to introduce and evaluate the use of SFRP materials to the field of structural rehabilitation. The SFRP procedure is versatile, rapid, not at all labor intensive and requires relatively little preparation of the surface to be repaired. Potential uses of such a rehabilitation system include:

1. Stabilizing deteriorated structures including those in a marine environment.
2. Increasing load capacity and improving serviceability conditions of deteriorated structures.
3. Retrofitting existing structures, particularly where structural continuity is required such as in unreinforced masonry structures.
4. Retrofitting and repairing historic or architecturally sensitive structures.
5. Protecting personnel and infrastructure from the effects of impacts and blasts

A distinct advantage of the SFRP procedure is its versatility. Such a technique may be used:

1. With little disruption to use and occupancy of the surrounding environment.
2. With relative ease under difficult to access conditions.
3. In less-than-optimal environments.
4. To repair structural elements having complex geometry.

PROJECT SUMMARY

Physical Characteristics of Deteriorated Reinforced Concrete Pipe Repaired with Epoxy Materials

This research was conducted to investigate the effect of a lining composed of Warren Environmental P301 epoxy system on the three edge bearing strength (ASTM C497) of cut sections of steel reinforced concrete pipe (RCP) which had been subjected to deterioration. Additionally, the effect of the presence water on the pipe walls during the repair procedure was also investigated. An evaluation of the bond between epoxy and the RCP substrate was also conducted.

Five 18 inch diameter Class IV-wall A (*per* ASTM C76) precast pipes, eight feet in length, were subjected to three different levels of damage, repaired using the P301 epoxy material, and finally cut into 12 inch sections. Twelve of the cut specimens had no damage, eleven where lightly damaged with an acid wash, and the final nine specimens were heavily damaged using mechanical degradation and an acid wash. The pipe wall of these specimens was reduced approximately one half inch at the crown. This damage was repaired with the Warren Environmental M301 mastic material, and the P301 epoxy coating was applied to the interior of the pipe.

The following conclusions were made:

1. The approximately 25% reduction of the pipe wall thickness at the crown resulted in a 5% decrease in the three edge bearing strength. Both, the repaired and non-repaired specimens displayed this decrease in strength.
2. The specimens damaged only by an acid bath but without any reduction in wall thickness did not exhibit any indications of a loss of strength. In the context of this work, these specimens are treated as non-damaged specimens.
3. Strength lost due to degradation of the interior surface of the pipe can be restored with the application of the epoxy system used in this program. The presence of the epoxy material resulted in a 20% to 26% increase in strength over an un-damaged, un-repaired section of pipe.
4. The presence of significant amounts of moisture during the application of the primer coating and epoxy produces a lower three edge bearing strength than specimens repaired in the dry condition. Some characteristics of debonding were exhibited in the failure of these specimens. Nonetheless, the strength of the repaired specimens still exceeded that of the virgin specimens.
5. The effects of initial damage and the presence of moisture during application of epoxy materials did not significantly affect the results of three edge bearing test.
6. The thickness the epoxy layer on a concrete specimen controls the pull-off strength (ASTM C4541) of non-cored specimens. This is not true for cored specimens, which produce consistent results regardless of coating thickness. This is a critical consideration when considering *in situ* acceptance or performance testing.
7. Repair in the "wet" condition caused debonding between the concrete surface and the epoxy material, while specimens repaired in the "dry" condition failed through the concrete in tension.
8. Specimens that were not repaired with any initial primer treatment exhibited lower pull-off strengths.

Surface Condition	Damage Condition	Three Edge Bearing Test (ASTM C497) Capacity of Repaired Condition to...		
		Initial Condition with Same Damage Level	**Undamaged Control Specimen**	**Similar Dry Condition**
Control	None	100%	100%	
	Heavy	100%	95%	
Dry	None	126%	126%	
	Heavy	131%	124%	
Wet	None	120%	120%	95%
	Heavy	121%	114%	92%

Table 1 – Percentage increase in three edge bearing capacities.

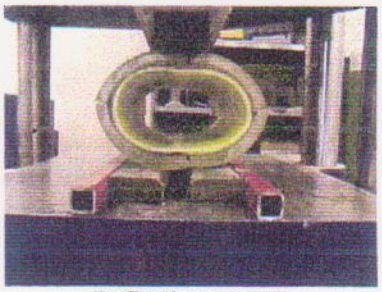
PROJECT SUMMARY

Physical Characteristics of Asbestos Concrete Pipe Repaired with Epoxy Materials

This research was conducted to investigate the effect of a proprietary epoxy material on the three edge bearing strength (ASTM C497) of cut sections of 6 inch diameter asbestos concrete pipe (ACP). Eight 12 inch long sections of 6 inch diameter ACP were tested. The pipe had a nominal inside diameter of 5.75 inches and a wall thickness of 5/8 inch. All specimens had been recovered from an installation of unknown age and appeared to be in good shape. Four specimens were lined with a proprietary epoxy material having a nominal thickness of 3/16 inch. The remaining four specimens were tested as control specimens. All specimens were submerged in potable water for 22 days prior to testing. Specimens were tested in a wet condition.

Failure of pipe (deflection = 0.81")

The ASTM C497 three edge bearing strength of the lined pipes was 16% greater than the unlined and showed less variation.



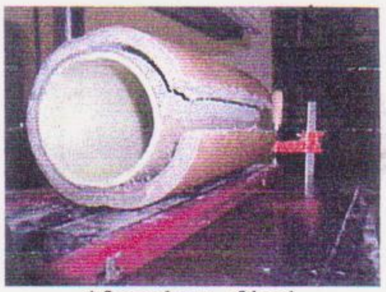
Deflection = 1.39"

The ACP tested has three layers: 1/8 inch outer and inner layers sandwich a 3/8 inch inner layer. The outer layers are more flexible. The initial cracking occurs in the inner layer and propagates to the layer interface. Generally, the failure then propagates along the interface, effectively delaminating the pipe around its circumference.

Deflection = 1.79"

The failure mode of the specimens having a 3/16 inch layer of epoxy on their inside surfaces was very similar. It was observed that the epoxy liner did not appear to be engaged when the pipe failed. No evidence of the damage to the liner was evident at pipe failure. In order to investigate this behavior further, one lined specimen was deformed beyond the point of pipe failure to investigate the ultimate behavior of the epoxy liner. The series of photographs documents this process. It is clear that even following the large deformations, the epoxy lining material remains intact. The residual three edge bearing capacity at this stage is approximately 20% of the ultimate capacity of the lined pipe and about 23% of the ultimate capacity of the unlined pipe.

The presence of the epoxy liner resulted in a small increase in load carrying capacity and did not appear to affect the stiffness of the pipe. Therefore, a corresponding small increase in deformation capacity was observed.



After release of load.