SYNTHETIC FIBER REINFORCEMENT FOR THE CAST IN PLACE FINAL TUNNEL LINER AT THE EUCLID CREEK TUNNEL PROJECT

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ABSTRACT

The Euclid Creek Tunnel is largely a precast concrete, segmentally lined, single shield driven CSO tunnel. The launch chambers, consisting of a tail and enlarged starter tunnel, were excavated by a roadheader in advance of the TBM arrival. After the TBM drive was completed, these launch chambers required a cast in place final liner that was originally designed with a single layer of circumferential and longitudinal reinforcing bars. This paper reviews the program to substitute a wholly plastic fiber-reinforced final lining in lieu of the reinforcing steel, including design, testing, construction and challenges of implementation.

INTRODUCTION

The Consent Decree and Project Clean Lake

The historic June 1969 Cuyahoga River fire sparked national interest in developing the federal legal framework for improved water quality. Congress passed the Clean Water Act into law in 1972 to improve and maintain the nation's water bodies through the elimination of pollutant sources. About the same time, the city of Cleveland created the Northeast Ohio Regional Sewer District, hereinafter referred to as NEORSD, to plan, finance, construct, operate and maintain pollution control measures.

As with many cities in the nation, when a storm event occurs, the inundation of the sewer system causes an overflow situation that result in discharges to the local water systems. To greatly diminish the impact of these events, the NEORSD entered into an agreement with the Ohio EPA (among others) called Project Clean Lake. Project Clean Lake is a twenty five year plan to reduce CSO overflow to Lake Erie and tributaries and has three major components. The first is green infrastructure, which seeks to keep storm water from various hard surfaces which, in turn, take storm water to the sewer system. The second is through improvements to area water treatment facilities. The third component is a system of conveyance and storage tunnels strategically aligned with existing overflow outfalls.

The Euclid Creek Tunnel

The Euclid Creek Tunnel (ECT) is the first of seven storage and conveyance tunnels in the Project Clean Lake program. The tunnel runs generally northeast southwest in direction, paralleling the shoreline of Lake Erie on the east side of Cleveland. The

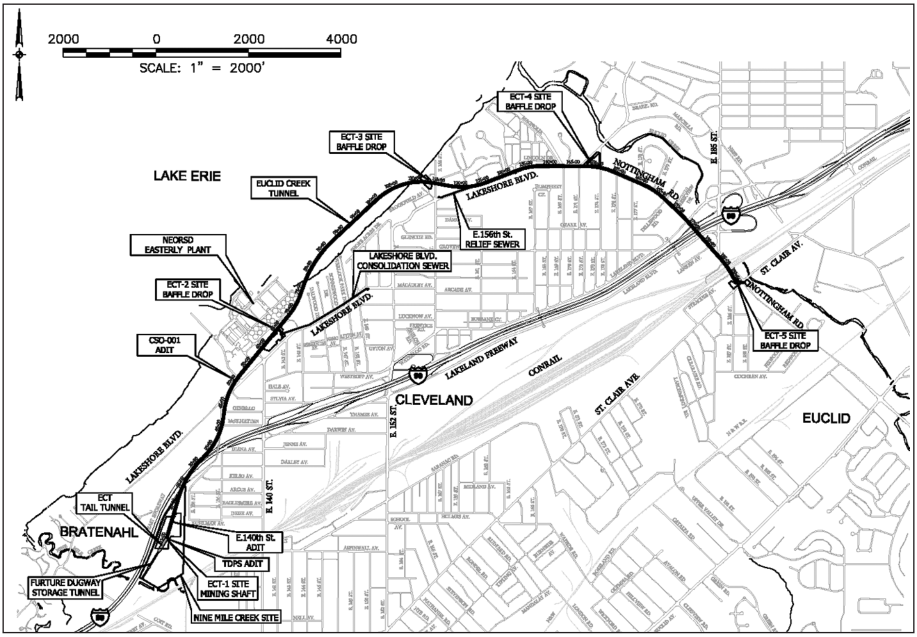

Figure 1. Euclid Creek Tunnel project layout

tunnel's eastern terminus is near Euclid Creek, while the western terminus is near the Easterly Waste Water Treatment Plant. The tunnel, along with supporting near surface infrastructure, intercepts CSO outfalls to both Lake Erie and Euclid Creek, provides storage for 52,000,000 gallons, and conveys the untreated water up to 17,750 feet. The project alignment is shown in Figure 1 including the Nine Mile Creek site with the mining shaft and the four baffle drop shafts used to direct storm water to the tunnel.

To provide the needed storage capacity, a 24 foot diameter tunnel was required. Design of the tunnel included steel fiber reinforced precast concrete segments for the main reach. With a segmental tunnel over three miles long, excavation by tunnel boring machine was necessary. The contract also required a 300 foot long tail tunnel, going in the opposite direction of the Euclid Creek Tunnel. This tail tunnel provides for a future connection point to the Dugway Storage Tunnel, the second in the series of seven under Project Clean Lake. A 30 foot diameter starter tunnel of 125 feet in length was also constructed in order to provide the necessary launching chamber for the TBM and conveyor systems. Unlike the majority of the storage tunnel, the tail and starter tunnels were designed with a final liner consisting of cast in place concrete.

The launching tail and starter horseshoe shaped tunnels are supported with pattern rock dowels and a three inch layer of shotcrete. This pair of tunnels was excavated by conventional methods utilizing a 105 ton class roadheader in a top heading and bench configuration. Utilizing a roadheader brings with it two important variables pertinent to subsequent final lining techniques. The first variable is the ability of the operator, machine, and guidance system to cut the desired profile. The second variable is the nature of the Chagrin Shale to experience overbreak. Normal overbreak is from 0 to 30 inches, but could be significantly more if the round, or unsupported, length is increased beyond 8–10 feet for a typical advance.

The Chagrin Shale does not give up meaningful amounts of groundwater when considering the excavation means and methods, however, it does yield some water and must be considered in the final lining design.

The ECT project team consisted of the owner, NEORSD; general contractor, McNally-Kiewit ECT joint venture (contractor); and owner's engineer, Hatch Mott MacDonald (HMM). NTP was issued in April of 2011, the starter and tail tunnel excavation took place from November 2011 to March 2012, and the final lining was placed from March to May of 2014.

ANALYSIS AND ORIGINAL DESIGN OF TAIL AND STARTER TUNNELS

The analysis that formed the basis of the original design was a rock load of 2,240 psf and external hydrostatic water pressure equivalent at ground surface, or 12,600 psf. Through different variations of modeling and application of asymmetrical loading criteria, the final design of the cast in place lining was determined to be a minimum 16 in. thick 6,000 psi compressive strength concrete lining reinforced with an inner mat of steel bars. Reinforcement selected was no. 8 bars on 12 in. center to center spacing each way.

The designed 6,000 psi underground structural concrete mix included additional requirements: water to cement ratio of 0.35, air content between 5%–7%, and 5%–10% by total weight of cementitious material for silica fume. Underground structural concrete is required to contain 5%-10% of the pozzolanic material silica fume for the enhanced hardened concrete durability and decreased permeability. Air content was selected for optimum freeze/thaw resistance.

CONTRACTOR PROPOSED LINING REINFORCEMENT

To reduce costs and shorten the schedule the contractor requested a change order be considered to replace the single layer of reinforcing steel with synthetic fiber reinforcement for the Tail and Starter tunnels. NEORSD, in fact, had been interested in a demonstration section to implement, test and monitor just such a technical approach and for potential economic benefits. The door was open for concept development, and the project team went about researching the groundwork for the proposed change.

The benefits of using synthetic fibers as perceived by the project team included the following:

- Eliminate the need to detail, fabricate, deliver, handle, place and tie reinforcing steel
- Separate operation of moving gantry to place and tie rebar not needed
- Simplify the wood bulkheads at end of forms—no penetrations
- Reduce the labor hours thereby reducing risk of injury due to exposure
- Reduce risk of injury by eliminating the need for laborers to be placed in awkward positions to place and tie reinforcing steel from a gantry
- Reduce pumping issues with synthetic fibers over steel fibers
- Improve long term durability and quality as there are no deteriorating effects from the oxidation of reinforcing steel

The challenges of using synthetic fibers as perceived by the project team included the following:

- How would a concrete mix with combined silica fume and synthetic fibers act when pumping over a distance and would the resulting workability be sufficient for the end product?
- What flexural strengths could be achieved with the local mix and would these strengths be consistent, repeatable, and sufficient for the final lining load conditions, or would the mix design need to be adjusted?

- How would the requirement to utilize silica fume dosed in the final lining mix affect the performance of fibers and could all other concrete requirements be adequately met; air content, slump, compressive strength?

ACI Committee Report 234R-06 “Guide for the Use of Silica Fume in Concrete” reports several impacts resulting from including silica fume in fresh concrete. The contractor must account for these fresh concrete property impacts during placement operations, which include the following:

- Water demand of concrete containing silica fume increases with increasing amounts of silica fume.
- Slump must be increased to achieve the same workability as silica fume-free concrete.
- Air entraining admixture dosage will increase with increasing silica fume to achieve the desired air content.

In addition to reduced workability and pumpability resulting from silica fume, adding synthetic fibers compounds the workability and pumpability challenges. Although the plastic fibers selected don’t absorb water, the fibers themselves offer a large surface area that attracts and collects cementitious paste—paste that would otherwise be available to effectively lubricate the concrete delivery pipe.

One final promising note from *ACI 234R-06* is in Chapter 5.2.5 which states, “Development of flexural and splitting tensile strengths of concrete incorporating silica fume are similar to concrete without silica fume.” This is important, as the flexural strength of the fiber reinforced concrete is the cornerstone of the principle of replacement of the rebar reinforced cast in place concrete tunnel lining.

Fiber selection was a little simpler for the contractor at Euclid Creek. Extensive plastic fiber testing was performed by Madsen et al 2009. Based on these published results, the contractor initially selected the same synthetic fibers for ECT Tail and Starter tunnels. The applicability of this initial selection was later be confirmed by tests performed on-site using 11.8 lbs/cy of synthetic fiber dosing rate.

To address the challenges and concerns with using synthetic fibers with silica fume for a deep underground tunnel final lining, testing was performed. The most representative results can be obtained when lab trials match field production in every aspect possible. The two most important aspects are replication of the chemistry of the mix and replication of the mechanics of batching and delivery. So it was important to utilize the same batch plant that the tunnel concrete mix comes from, same ingredients, same fiber dosing technique for mix trials and production concrete, using the same mixer trucks, and same delivery distance.

The batch plant utilized the typical central drum mixer style where a conveyor extends from the sand and aggregate towers to the central mixer. The plant is constructed with a mezzanine level at the same height as this transfer conveyor. It is from this mezzanine that the bags of silica fume and synthetic fibers are dosed onto the belt for each batch. For the trials, a three cubic yard batch was the smallest size the plant was comfortable making within the guidelines of their quality control program and be within their desired weight tolerance targets. Three cubic yard batches were made on three consecutive days and sent to the ECT jobsite. This was done in this manner to show repeatability of the process, and to experiment with plasticizer dosing rates for workability.

The first day was batched with no plasticizer, the second day a half dose of 32 oz/cy, and the third day a full dose of 64 oz/cy. Six test beams were made from each day’s batch at the ECT project site following guidelines provided in ASTM C1609. The results from the three days of trials are presented in Figure 2.

The trials were run in late October, 2013, and proved reliable for repeatability. With the addition of plasticizer to the mix, a four inch slump and acceptable air content

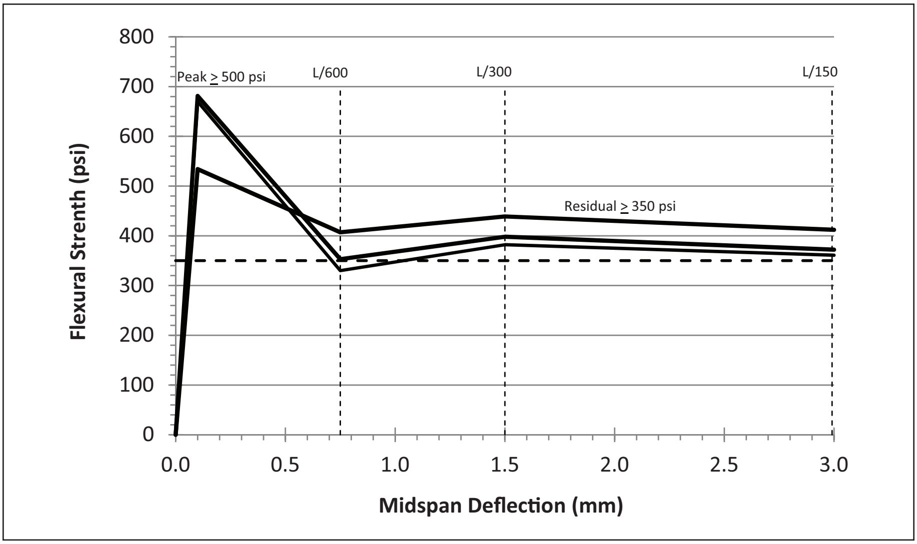

Figure 2. Flexural strength results for trial batches (ASTM C1609)

could be produced. With the known aggregate size and the batched concrete slump in hand, and effective concrete pump and delivery system could be devised. Cylinders and beams were cast from the trial batches. Cylinders were tested at the local testing laboratory but beams had to be transported to the University of Michigan, Department of Civil and Environmental Engineering, Ann Arbor. Test beams were maintained in cure tanks on the ECT jobsite for 27 days then driven to Ann Arbor, MI from Cleveland, OH (approximately 3 hours) in wet burlap wraps.

With the trials complete, the project team jointly agreed on the following concrete acceptance criteria:

- $f'_c \geq 6{,}000$ psi
- F1 ≥ 500 psi (first crack flexural strength)
- F300, 1.5 ≥ 350 psi (residual flexural strength at deflection L/300)
- Air content between 5%–7%
- Slump 4 inch target

CONSTRUCTION

Concrete placement operations for the Tail and Starter tunnels occurred during March, April and May of 2014. Forms utilized were 24 foot diameter full circle telescoping forms, equipped with a form carrier and needle beam. The carrier could handle 32 foot long sections of formwork, and the contractor chose to use two sections of formwork for the cycle, making a 64 foot long pour. Forms were set up for the first pour at the farthest point from the access shaft. Bulkheads were constructed on both ends of the first form placement.

The Starter and Tail tunnels when first excavated were mined with a roadheader. Along with the minor scallops that occur with over excavation, the shale exhibited occasional overbreak, as well. Normally, full circle telescoping forms are purchased for long smooth bore TBM drives and are built to withstand the pressures of a full hydrostatic pour. So for the Euclid tunnels to take advantage of the form pressure design capacity,

Figure 3. Form set up for first placement

full well knowing there were some large pours to be made from 600 to 900 cubic yards, the best option is concrete delivery by pumping.

The equipment decisions for pumping a highly dosed plastic fiber reinforced concrete with crushed aggregates as large as passing a 1 inch screen are uncharted and less documented at best. Given a 600 foot pumping distance, numerous bends through the placer car, and an overpressure requirement to fill the crown of the forms, this was no certain task. Not only was the pumping pressure to move a stiff concrete with large aggregates a risk, but fiber balls were certainly a risk. One good sized fiber ball gets in the slickline and 200 feet of shaft slickline gets plugged would be a difficult situation to quickly recover.

Concrete was delivered with a Putzmeister 36Z concrete pump truck with the higher powered 16H 9 inch piston pump. The boom on the truck was not employed, instead the output line was reduced from a 6 inch to a 5 inch diameter, run through a thrust block, elbowed down the 200 vertical foot shaft. At the bottom of the shaft, a pneumatic squeeze valve was installed, and this would keep the shaft line full so the pressure from the concrete head in the shaft. After the shaft to tunnel elbow, there was another thrust block installed. The slickline then ran into the tunnel on the invert, through a hose, and into the placer car.

The fear of the fiber ball plugging the line remained. Since the fibers were slightly less than 2.5 inches long, it was decided to place a one way bar grate over the concrete hopper spaced at 2.5 inch centers. It was planned to have two laborers stationed at the chute/hopper transfer point in order to watch for any potential fiber balls.

On the first pour day, the grating on the pump hopper quickly became the big issue. The concrete would barely flow through the grating, but the grating did catch a couple of 6 to 8 inch diameter fiber balls. It was apparent that the grating could not be removed completely for that reason. When the concrete level in the hopper was below the grate, the laborers had to punch the wet fiber concrete through the grating with shovels. The pump would slow or the concrete delivery would speed up, and the hopper filled up above the level of the grating. At this point the mixer truck would stop delivery by regulating the direction of the mixer drum. In a short time, the pump would catch up, but it wouldn't be obvious as the concrete on top of the hopper would not fall through the grating—it was simply running the pump dry underneath but out of view. The operation was shut down after a few hours placing 70 cy of concrete fighting this condition. The

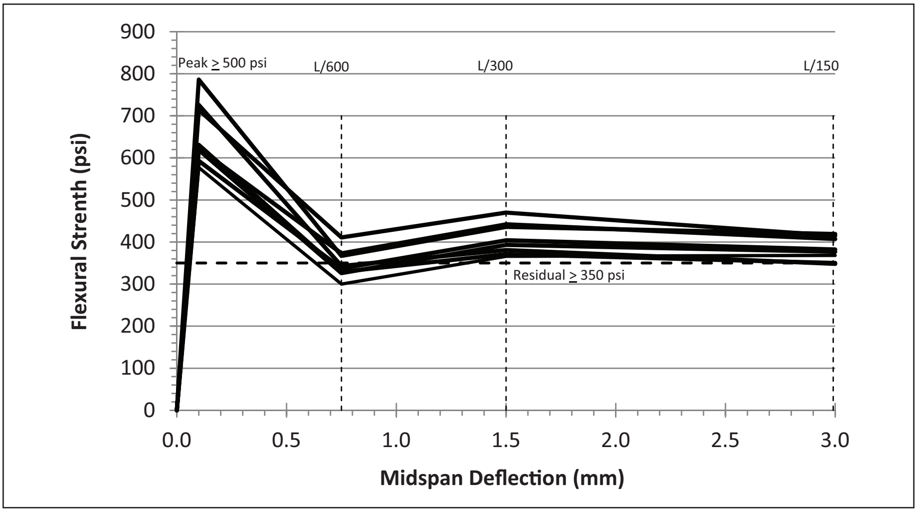

Figure 4. Flexural strength results for tests performed during tail and starter tunnel pours (ASTM C1609)

grating on the pump hopper was expanded to 5 inch centers and the remaining 430 cy pour was successfully completed the following day. The laborers at the pump hopper became very important to collect the few fiber balls that were encountered.

One item of note, the shutdown in the first pour to make the grate adjustments created an unplanned construction cold joint. In the interest of quality, a green cut was performed with compressed air and water, to prep the joint for the follow on pour. This is not advisable with synthetic fiber reinforcement. The green cut operation loosened all the fibers that were embedded at the joint and washed them down into a giant ball at the lowest point below the formwork. Before the pour started again they had to be removed to prevent a large, shaggy void in the tunnel lining. The joint should have been left as-is, with the fibers promoting the bond in the joint, not green cut from the joint.

The second and all subsequent pour days went fine. The 5 in. spacing on the hopper bars were just right to catch the big fiber balls but also allowed the concrete to move freely to feed the pump. The pump rarely struggled and typical line pressures were 70–90 bar. For this and the remaining pours, concrete could be placed as fast as the bulkhead design and the batch plant would allow.

Figure 4 shows the eight test results from the seven concrete placements. Three beam test results are averaged together to make a test result. All the test results passed both the first crack and residual flexural strength requirements.

Figure 5 shows the flexural strength normalized by the square root of the unconfined compressive test for all tested samples. The average normalized flexural strength ratio is 7.7 and minimum result was greater than 6. By comparison, American Concrete Institute (ACI) provides design ratios of 7.5 for modulus of rupture and 5 for direct tensile strength.

The cast in place final lining operation is considered a success by the entire project team. Concrete tests proved the end product met engineering requirements, NEORSD now has a background with the technology with plans to implement synthetic fiber use in the future, and the contractor met schedule with the selected equipment. Minor crack repair was required in a few places, but no more so than traditional lining reinforcement. Patching was required at the float pin points, but no large pockets of poor concrete consolidation were encountered.

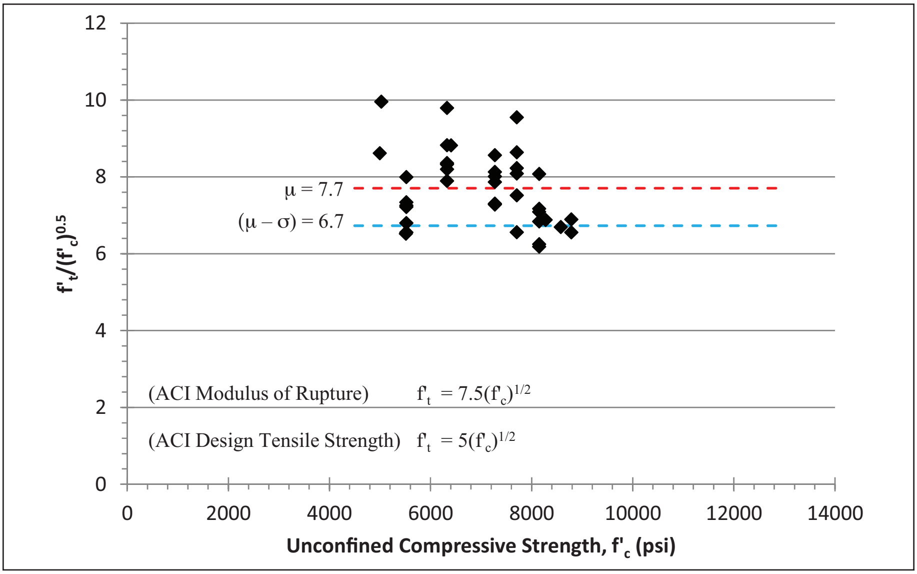

Figure 5. Normalized flexural strength results for tests performed during tail and starter tunnel pours (ASTM C1609).

CONCLUSION

Synthetic fibers, under the right rock load and hydrostatic conditions, are and effective reinforcing technique vis-à-vis engineering requirements, improved long term product quality, and cost effective, safe construction methods. Test on both the trial mix designs and the production concrete indicated that both first crack and residual flexural strengths could be achieved and maintained through the project life cycle. Synthetic fibers offer the NEORSD a more corrosion resistant final product, especially considering the harsh environment of a combined sewer system. Finally, with the right equipment and hardware for pumping and controls on the delivered fresh concrete, a fast, efficient and labor friendly method of placing reinforced cast in place final tunnel liner can be achieved.

REFERENCE

Madsen, Decker, Zeidler, Gall, O'Brien, 2009. "Experience with Synthetic Fiber Reinforced Initial Shotcrete Lining at the Devil's Slide Tunnel Project," *Spritzbeton-Tagung*, in Alpbach, Austria, January 15–16.