The Art of Tunnel Rehabilitation with Shotcrete

by Harvey Parker, Paul Godlewski, and Roberto Guardia

The art of rehabilitation of tunnels has flourished and developed significantly over the last couple of decades. Several hundred railroad, highway, and conveyance tunnels have been successfully rehabilitated, converted, and/or enlarged. Much of this development can be attributed to the successful use of steel fiber-reinforced shotcrete. The flexibility and adaptable nature of steel-fiber microsilica shotcrete is ideal for rehabilitation of tunnels. Thanks to shotcrete, enlargement and rehabilitation of tunnels without fully taking the tunnel out of service is not only technically but also economically feasible considering the cost of other alternatives including the "do nothing" alternative. Enlargement was usually accomplished by raising the crown but some have been enlarged by lowering the invert, which is much more difficult and time-consuming.

Introduction

One of the advantages of tunnels is that they inherently last much longer and require less maintenance than other infrastructures. The authors have rehabilitated several tunnels that were over a century old, allowing these tunnels to begin their second century of service. This long life represents a huge life-cycle benefit for the tunnel owner, and this cost advantage can be maintained by conducting an occasional rehabilitation from time to time. The increase in the number and type of tunnels being rehabilitated over the last few decades was largely made possible by the continued development of ground support methods using rock bolts and steel fiber-reinforced shotcrete.

Rehabilitation is done for several reasons. Sometimes rehabilitation work is done simply to extend life or to improve future performance, such as reduction of maintenance or to improve safety. Generally, highway tunnels, such as the one illustrated in Fig. 1, fall into this category.

Other reasons for rehabilitation include: 1) enlarge the tunnel to increase clearances or capacity or 2) change the type of tunnel from one use to another. Examples of the former are the hundreds of railroad tunnels recently enlarged to accommodate the bigger double-stack container cars. An example of the latter is the Berry Street Tunnel in Pittsburgh that was converted from an abandoned rail tunnel to a bus tunnel. The Whittier Tunnel in Alaska is another good example of a rail tunnel that was converted to a dual-use tunnel by installing signal systems and a roadway surface cars can travel on when trains, which run infrequently, are not using the tunnel.

The introduction of double-stack container cars and other special or extra-large cars (for example, tri-level auto racks) created a need for enlargement of most of the tunnels in the United States and Canada. This is an ideal example of tunnel rehabilitation to satisfy a need for larger tunnels and better service rather than just to extend their lives.

Many of the railroad tunnels in the west and several on the east coast have been enlarged by increasing clearance in the crown. Clearances were improved mostly by crown mining, which consisted of either cutting a notch in the existing lining or rock walls, as shown in Fig. 2, or by complete or substantial removal of the brick or concrete lining.

Where needed, state-of-the-art linings consisting of steel-fiber microsilica shotcrete, rock bolts, and, in some cases, lattice girders or steel sets were installed. Moreover, most of this work was done without taking the tunnel out of service.

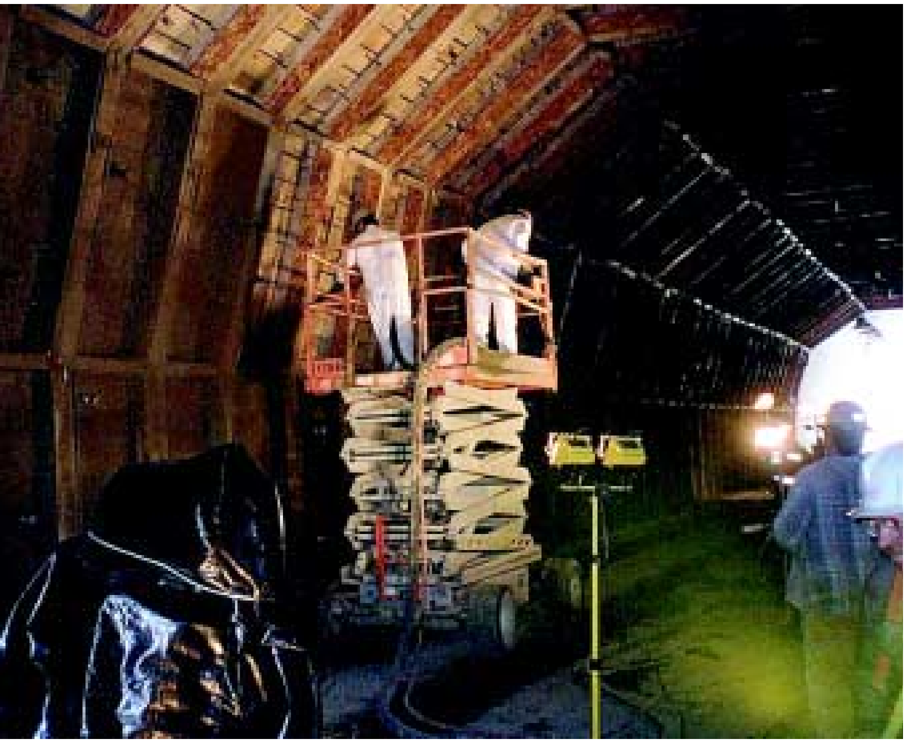

Figure 1: Shotcreting for rehabilitation of highway tunnel.

Several hundred tunnels comprising over 50 miles (80 km) of tunnels, ranging from less than 100 ft (30 m) to over 7 miles (12 km) in length, were rehabilitated and/or enlarged in the last few decades. Though most of these tunnels were railroad tunnels, several highway tunnels have also been rehabilitated or enlarged under "live traffic conditions." Moreover, there have been many hydro and sewer tunnels inspected and then rehabilitated.

Naturally, the tunnels that have been rehabilitated comprised a full range of existing conditions and serviceability and were constructed by a wide variety of construction methods using several different materials. The size and shape and construction method depend on the type of tunnel. However, there are some general trends described as follows. Experience shows that even poorly constructed and poorly maintained tunnels can be successfully rehabilitated.

Keeping the Tunnel in Service During Rehabilitation

Tunnels are vital to keeping our transportation systems going, and interruptions of service are rarely permitted. Rehabilitation that requires invert work usually shuts the entire tunnel down. It is better to concentrate tunnel rehabilitation on the crown and sidewalls if at all possible. Typically, there are no alternate routes so tunnel work must be done with the least disruptive effect on paying traffic. This is done by either temporarily shutting down one lane or one track in multiple lane/track tunnels or by managing traffic to permit work windows that might last from 1 to 8 h. Yes, work can be accomplished in windows of 1 or 2 h; it is not very efficient but sometimes that is all the time one can get in any one work window.

Rehabilitation work while keeping the tunnel in service requires enormous planning, coordination, and selection of proper construction methods. The flexibility of shotcrete, especially with volumetric mixing, is extremely valuable to tunnel rehabilitation. Usually, all work is done from work platforms designed specifically to make all the work (including handling muck and rebound) done as efficiently as possible. A schematic of a special work train that is used for railroad tunnel rehabilitation is shown in Fig. 3.

Figure 2: Tunnel clearance notch in a railroad tunnel.

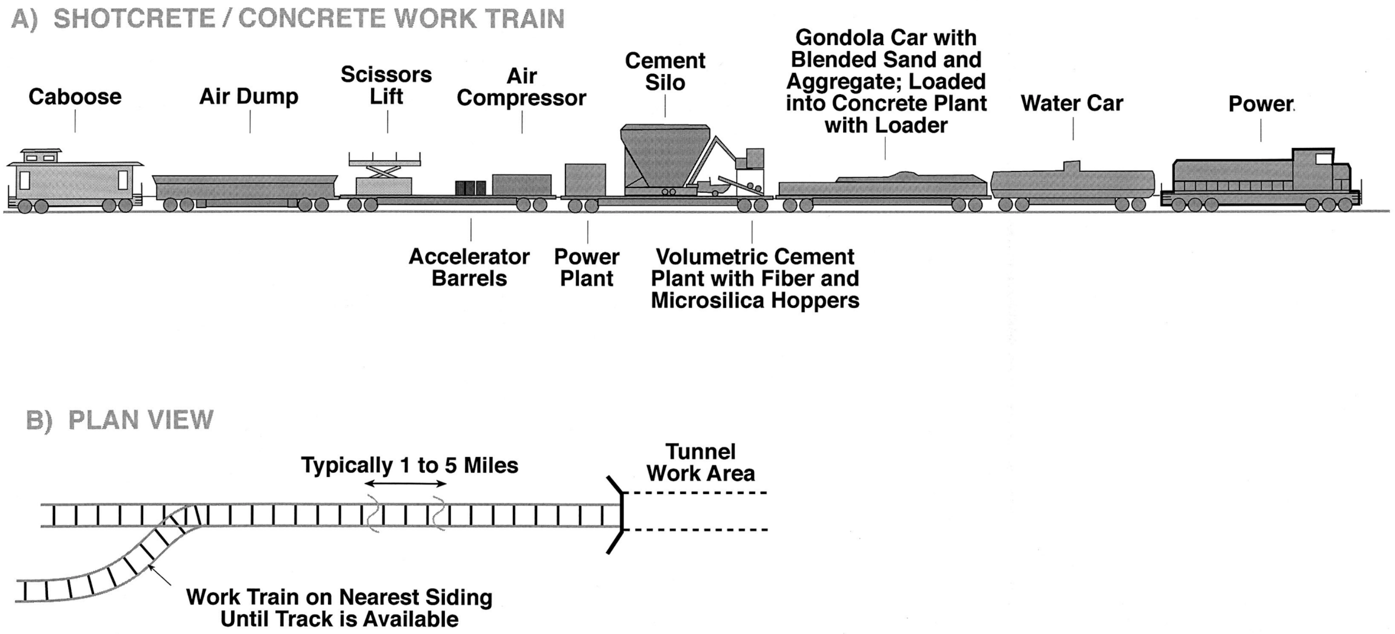

Figure 3: Typical railroad work train schematic.

Figure 4: Sling bags of shotcrete mixture and work train at a railroad siding.

The work train stays on a nearby siding (refer to Fig. 3 inset) until dispatchers give the work train clearance to move onto the main track and travel to and stay in the tunnel site for a specific limited period of time. Similar methods are used for highway tunnels using rubber-tired equipment.

Advantages of Shotcrete

Steel fiber-reinforced shotcrete offers the flexibility needed to adapt to rapidly changing ground conditions and uncertain work window schedules. In some projects, due to the remote location, a concrete batching plant is not available. Shotcrete dry mix including steel fibers and microsilica can be purchased in prepackaged 1 y^3 (0.75 m^3) bags (sling bags) and conveniently stored at the site until needed (refer to Fig. 4). Usually the dry mix is batched at a centrally located plant where the quality of the shotcrete mixture can be controlled before shipping to the site. Shotcrete from sling bags can be placed by the dry or wet method.

When placing steel fiber-reinforced shotcrete in tunnels, costly steel or wood arch forms, and even rebar or mesh, are not required. Time is not wasted while erecting, curing, and removing forms or hassling with mesh. Shotcrete will conform to the rock surface and smooth out the irregularities caused by blasting. In cases where the tunnel rock is locally unstable, the design ground support can be increased to carry the unbalanced load. Additional shotcrete and rock bolts are placed as necessary to stop movements as documented by monitoring.

Shotcrete can be finished with a trowel to a smooth surface equivalent to a form finish. In a pedestrian tunnel, shotcrete was placed in the steel reinforced arch of the horseshoe-shaped tunnel and elegantly finished to a smooth surface. In tunnel sidewalls, the presence of steel fibers on the surface could cause scratches on the arms of pedestrians. In these situations, the last 2 in. (5 cm) of shotcrete are placed without steel fibers. Typical shotcrete specifications for mixture proportioning indicate that each cubic yard contains a minimum of seven and a half sacks of cement (420 kg/m^3), 80 to 100 lb (50 to 60 kg/m^3) of steel fiber, 80 lb (50 kg/m^3) of microsilica, and a coarse aggregate/total aggregate ratio of 0.4. The compressive strength of these mixtures exceeds 5000 psi (34.5 MPa) in 28 days. The fiber content can be adjusted higher or lower as necessary to accommodate the ground conditions.

Examples of Rehabilitation Using Shotcrete

A railroad tunnel in the eastern United States was enlarged from a single-track tunnel to a twin-track tunnel. Originally lined with brick, the tunnel was

Figure 5: Railroad tunnel clearance excavation: single to double track.

taken out of service and enlarged to obtain the double-track clearance. The new liner consisted of steel fiber-reinforced shotcrete and rock bolts. Shotcrete thickness varied from 4 to 12 in. (10 to 30 cm). Typical rock bolt lengths were 12 ft (3.7 m) but in places ranged up to 18 ft (5.5 m) long. Figure 5 shows the excavation process and the shotcrete liner. The tunnel encountered open abandoned coal mine works, and the flexibility of utilizing shotcrete and tensioned rock bolts was invaluable in advancing the work through difficult ground.

A highway tunnel on the west coast was rehabilitated because of the limited clearance and continued deterioration of the timber lining. The liner consisting of timber sets and lagging was replaced with 4 to 5 in. (10 to 13 cm) of steel fiber-reinforced shotcrete in the arch and 2 to 4 in. (5 to 10 cm) of concrete on the sidewalls. Rock dowels anchored with epoxy resin cartridges were installed after an initial layer of shotcrete was installed.

In one area of heavy ground, after installing a temporary support consisting of 6 in. (15 cm) of shotcrete and rock dowels, steel sets were erected on a 4 ft (1.2 m) spacing. Expanded metal was installed as concrete forms between the steel sets and, after placing concrete between the steel sets and the initial support, the perimeter of the tunnel was covered with a layer of shotcrete.

At the portals, shotcrete was installed in conjunction with a waterproofing system. After installing the initial tunnel support, the polyvinyl chloride (PVC) membrane was attached and steel lattice girders were installed on a 3 ft (1 m) spacing. Steel reinforced shotcrete up to 12 in. (30 cm) thick was then placed in and between the lattice girders.

Another western highway tunnel was originally built with timber sets and lagging. Backpacking consisted of minus 4 in. (10 cm) rock below the springline and cordwood above the springline. Loosening of the rock wedges increased the loading and caused significant deformation of the timber lining. The misaligned timber sets encroached highway clearance and trucks started hitting the timber sets.

Rehabilitation consisted of shotcreting over the timber sets and cement grouting the unstable rock and cordwood behind the liner. In addition, the depth of the timber sets was reduced by 6 in. (15 cm) after shotcreting in between the timber sets, over the lagging. Steel fiber-reinforced shotcrete was placed in two stages, the first one before the grouting and the second one after grouting and set trimming was completed. Figure 1 shows the installation of the initial layer of shotcrete and the grout pipes extending through the timber lagging. The existing liner served as the formwork for the new shotcrete liner, and it was determined that permanently encapsulating the existing liner was acceptable.

The method of rehabilitation of timber-lined railroad tunnels varied somewhat from tunnel to tunnel, but, in general, after the work train left the siding and arrived at the next tunnel requiring rehabilitation, the rock and lining would be inspected and decisions made as to the type and amount of support that would likely be required. In cases where instability was expected, presupport by rock bolts would be installed. Then one timber set (usually spaced at 3 ft [1 m] intervals) would be pulled down with a cable, with a gondola or air-dump car placed under the set to collect most of the falling timber and rock (refer to Fig. 6).

After the dust settled, the section would be inspected from the safety of the previously installed lining and a decision made by the resident engineer as to the final location of rock bolts and amount of shotcrete required. Immediately, the rock surface would be scaled and washed, and bolts and shotcrete would be installed, making the section safe for the passage of trains. This work was all done during the available work window of time. The resident engineer would then have to decide whether to advance another set during this or the next work window, or wait until the following day. Within hours after this photograph was taken, the area was bolted, shotcreted, cleaned up, and approved for the safe

Figure 6: Timber set removal in railroad tunnel.

passage of trains. This sequence gave lots of exciting and challenging days for the resident engineer and the rehabilitation crew but this slow, safe, and steady method was used to rehabilitate dozens of timber-lined tunnels under live-track conditions.

Conclusions

The use of steel fiber-reinforced shotcrete made the rehabilitation of railroad and highway tunnels practical and economically viable. The strength and durability of steel fiber microsilica shotcrete in combination with tensioned or untensioned anchor bolts can handle almost any type of tunnel ground loading. Shotcrete can be installed utilizing the wet or dry methods and can be installed to sculpt any tunnel shape without the use of costly forms or the need for rebars or mesh. No matter if 10 or 1000 y^3/m^3 of shotcrete are required, there is always an economical method of providing and installing quality and durable shotcrete.

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