*Proceedings*

*Shotcrete for Underground Support XI*

Engineering Conferences International *Year* 2009

# RECENT EXPERIENCES USING SHOTCRETE AT UNDERGROUND LABORATORY FACILITIES

Christopher Laughton PhD, PE
Fermi Research Alliance, Illinois, USA, laughton@fnal.gov

# RECENT EXPERIENCES USING SHOTCRETE AT UNDERGROUND LABORATORY FACILITIES

Eur. Ing. Christopher Laughton, PhD, PE, Project Manager Underground Design & Construction
Fermi Research Alliance
PO Box 500, Wilson Hall, MS-220
Batavia, Illinois 65010, USA
T: 1-630-840-5407; F: 1-630-840-3614; E: laughton@fnal.gov

## ABSTRACT

The paper discusses the use of shotcrete linings at underground laboratories, and details the application of shotcrete and water control systems on the Neutrinos at Main Injector project, located in Illinois, USA. The paper also proposes guidelines for the use of shotcrete at the Deep Underground Science and Engineering Laboratory, South Dakota, USA.

## INTRODUCTION

Stability and water control are key issues that commonly drive design decisions with respect to the choice and dimensioning of permanent underground linings. These issues are particularly crucial for underground laboratories, where long-term stability and watertightness are often prerequisites for experimental success. Such considerations can result in the adoption of substantial structures that incorporate fully-sealed waterproof membranes and cast-in-place concrete linings. For many ground conditions and research applications these linings may be overly conservative, unduly increasing the duration and cost of construction, and unnecessarily reducing the competitiveness of an experimental programme in the eyes of a funding agency.

Recently, underground researchers have increasingly turned to the use of shotcrete as a lining of choice. A relatively thin shotcrete lining, used in conjunction with other ground support and water control measures, can provide a stable opening that meets research requirements while providing greater flexibility in design and construction. The integration of shotcrete into the excavation cycle can also create opportunities to reduce the cost and time of construction through improved productivity and increased overlap of construction activities.

## UNDERGROUND PHYSICS LABORATORY FACILITIES

Over the past quarter century, a number of underground physics laboratory facilities have been constructed worldwide. These facilities house particle accelerators such as those sited at relatively shallow depths in soil and rock at the European Particle Physics Laboratory (CERN), Fermi National Accelerator Laboratory (Fermilab) and Stanford Linear Accelerator Center in the USA, and the Proton Accelerator Research Complex (J-PARC), in Japan. A number of deeper bedrock sites have also been developed to house particle observatories.

Design criteria for these underground laboratories vary significantly from site to site based on ground conditions, site constraints, experimental requirements and local practice. However, physics criteria often include a need for long-term foundation stability and an high degree of humidity control compatible with experimental end uses. To meet such demands a wide range of issues need to be addressed during the requirements setting and early design phases, as shown schematically in Figure 1. Shotcrete can offer cost-effective solutions to address many of these issues.

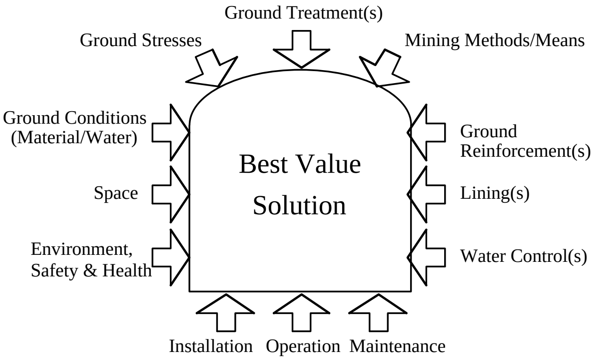


Figure 1: Key Issues to Consider in the Underground Design Process

Traditionally, underground physics laboratories have used cast-in-place linings. One such cavern structure is shown in Figure 2 (Laughton, 1990 1). The photo shows waterproofing and concrete lining operations for a 21m-span cavern constructed for CERN’s Large Electron Positron facility. The cavern was sited some 50m deep, below the water table, in a molasse bedrock. Rock bolts and shotcrete served as the initial ground support. A waterproof membrane and cast-in-place concrete lining were added upon completion of the excavation phase. Many shallow (<200m) physics facilities are housed in similar structures. These facilities have generally been sited in saturated soil and soft rocks, where stability and water-tightness have been difficult to achieve reliably without recourse to the use of massive structural members and composite waterproofing systems. At deeper, hard rock sites, shotcrete has been more commonly used as a permanent liner.

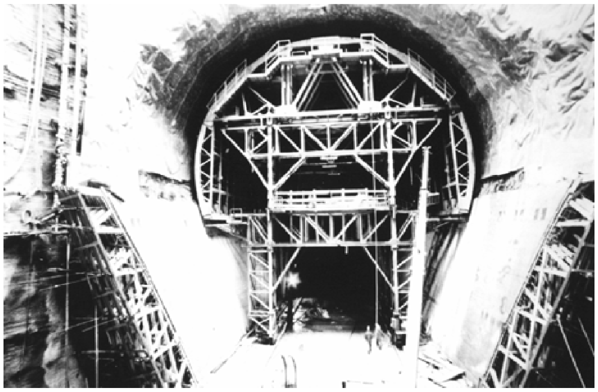


Figure 2: Waterproofing and Soffit Formwork In-Place for a Cast-in-Place Lining

Table 1: Deep, Hard Rock Physics Laboratory Facilities

| Laboratory Site | Depth, m | Vol., $m^3$ | Permanent Liner |
|---|---|---|---|
| Canfranc, Spain | 900 | 7,200 | Shotcrete/Wall Panels |
| Homestake, USA | 1500 | 18,500 | Wire Mesh only |
| SNO, Canada | 2220 | 19,600 | Shotcrete/Mineguard |
| Soudan, USA | 770 | 25,200 | Shotcrete |
| Kamioka, Japan | 1000 | 56,500 | Shotcrete/Concrete |
| SNOLab, Canada | 2220 | 73,000 | Shotcrete/Rockweb |
| Gran Sasso, Italy | 1440 | 180,000 | Shotcrete/Wall Panels |

Table 1 lists a number of laboratories constructed, at depth, within operating facilities, such as mines and transport tunnels. Approximate depths, mined volumes and permanent liner systems are noted. With the exception of the Homestake site, the laboratories have made extensive use of shotcrete. In addition to shotcrete, the deepest facilities, SNO & SNOlab, sited at the base of the Creighton Mine, received a thin, spray-on liner (Mineguard or Rockweb) applied to mitigate against rock burst behaviour (Lamour,2008 2).

## SHOTCRETE ON THE NEUTRINO AT MAIN INJECTOR PROJECT

The Neutrinos at Main Injector (NuMI) underground facilities is one of the first shallow-sited physics facilities to use shotcrete as a permanent lining. This particle beam facility is housed under the Fermilab site located 40 km west of Chicago, in northeastern Illinois. The neutrino beam generated at Fermilab passes through an on-site “near” detector, and continues on, through the earth, to a “far” detector located at the Soudan iron mine, some 732km to the northwest.

### The Tunnel Alignment

NuMI beamline components and the near detector are housed in a series of tunnels and chambers as shown in section on Figure 3.

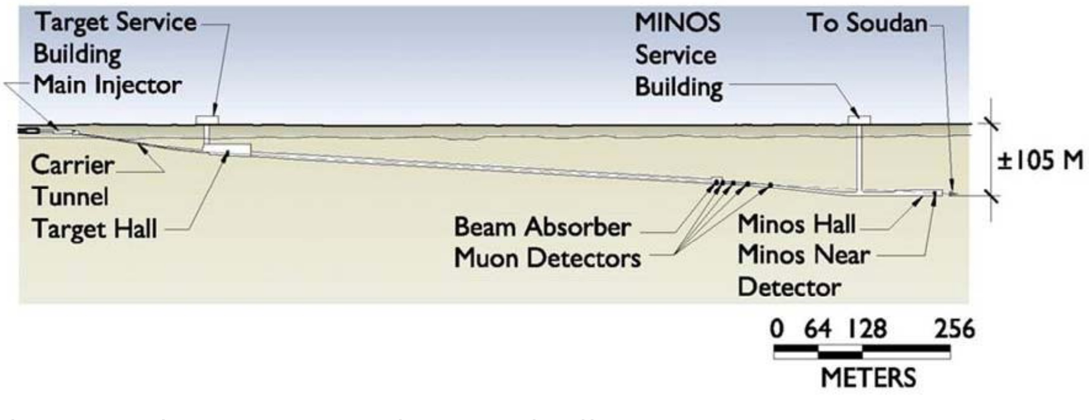


Figure 3: The NuMI Beamline Longitudinal Plot

The NuMI tunnels are aligned to allow proton beam transfer from an existing accelerator, the Main Injector. The particle beam passes through the Target Hall, Decay Tunnel and Beam Absorber, and onwards to a detector, housed in the Minos Experiment Hall. Upstream of the Target Hall, the beamline tunnels are inclined at slopes of up to 16 percent. This was the only section of tunnel over which there was alignment flexibility. Below the Target Hall, the beamline tunnel is precisely aligned so that the neutrino beam intersects the far detector, located in northern Minnesota.

The spans of the NuMI tunnels and chambers vary along the beamline from under 2m in soil to over 10m in rock. The cross-section of each underground structure was developed to meet region-specific radiation shielding, space and environmental requirements. Seven metre diameter vertical shafts, sited at either end of the complex, provide access and egress to the facility. Buildings atop of each shaft provide crane and elevator access, and electrical and mechanical service feeds.

## NuMI Rock Conditions and Underground Design Considerations

At the Fermilab site, a mantle of some 20m of glacial till overlies a sub-horizontally-bedded series of dolostone, siltstone and shale strata. Two widely spaced sub-vertical, orthogonal joint sets are present within these strata. From a rock engineering perspective, the NuMI host rock mass is characterized as “blocky”, with blocks delineated by joints and bedding. Pattern rock bolt reinforcement was laid out and sized to mitigate against blocky-rock fall-out. In early designs shotcrete was incorporated as a temporary support measure to prevent small-block fall-out, and inhibit the on-set of slake/swell behavior of shale and siltstone interbeds.

The NuMI openings lie at depths ranging from 15 to 100m below surface, within the regional aquifer. This aquifer is used as a source of domestic water and great care was exercised in its characterization and protection. Design mitigations were put in place to ensure that construction and operation of the NuMI facilities had no adverse impact on the quality or accessibility of the water resource. Water ingress and water table draw-down were limited through the use of pre-‘ and post-excavation grouting. Maximum steady state water inflow rates were specified in the geotechnical baseline document. Inflow rates estimated prior to cement grouting and allowed after grouting were identified in the construction contract for the different enclosure regions. These inflow rates are summarized in Table 2.

Table 2: Required Steady State Water Inflow Rate in NuMI Regions

| | Steady State Inflow Estimates l/min/lin. m | |
|---|---|---|
| Region | Pre-Grouting | Post-Grouting |
| Target Hall | 0.5 | < 0.1 |
| Decay Tunnel & Absorber Hall | 1.1 | < 0.3 |
| Carrier Tunnel | 2.1 | < 0.5 |
| MINOS Hall | 4.3 | < 0.5 |

Initial NuMI design work placed an heavy emphasis on defining end-user space, stability, shielding and dryness requirements. Once these criteria had been set, a site investigation campaign was performed to collect alignment-specific geotechnical data sets. Based on these data, engineering analyses were made to select practical excavation methods and means, predict ground behaviors and estimate the steady-state water inflow rates noted above.

Early underground design concepts, developed before an alignment-specific investigation had been undertaken, were based on the use of heat-sealed waterproofing and reinforced concrete as a permanent lining. Once the strength and durability characteristics of the host rock mass had been better defined, it was suggested that drained shotcrete linings could potentially meet requirements for stability and dryness, without recourse to a full structural lining. Alternate lining designs, based on the use of shotcrete, were developed for evaluation within the context of a value engineering (VE) review. As a result of the VE studies, a number of cast-in-place linings were replaced by shotcrete. Where implemented, the change from concrete to shotcrete was estimated to result in a cost saving for the lining function of roughly 25%. Ultimately, cast-in-place concrete was removed from all the tunnel designs. Structural concrete was only placed in shafts and tunnel inverts.

Laboratory conditions for water control and dryness were achieved through the use of a combination of engineering measures tailored to meet the operational requirements of each experimental region.

## Water and Humidity Control Measures

Table 3 shows the combinations of water and humidity control measures adopted in the different experimental regions of the underground facility. In Experimental Region 1 (Decay Tunnel, between Target Hall and Absorber Hall), a modicum of water inflow was maintained to address groundwater contamination concerns. Rates of inflow were controlled using pre-‘ and post-grouting; and drainage. Plain shotcrete was generally applied in tunnel reaches where personnel access was required.

Table 3: Water Control Measures In Different NuMI Beamline Regions

| | Experimental Regions | | | |
|---|---|---|---|---|
| Water Control Measures | 1 | 2 | 3 | 4 |
| Pre-‘ & Post-Grouting | • | • | • | • |
| Shotcrete & Drain Mat | | • | • | • |
| Drip Ceiling | | | • | • |
| Dehumidification | | | | • |

In Region 2 (access tunnels and utility passages), pre- and post grouting was required during excavation, and pattern and over-fracture drain mats were placed prior to shotcrete application. Drain mat strips were placed on a 5m square pattern. Individual water-yielding fractures (joints and bedding planes) were also covered with drain mats, as shown schematically in Figure 5. A 100mm layer of reinforced shotcrete was placed over all exposed rock surfaces and drain mats. The shotcrete lining had a uniaxial compressive strength of 30MPa. Reinforcement was provided by either steel fiber or wire-mesh.

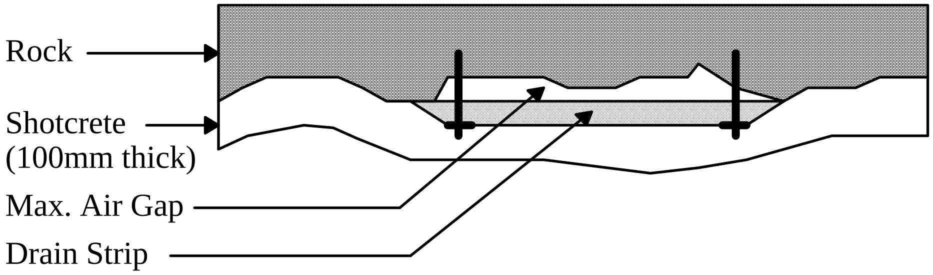


Figure 5: Detail of the Behind-Lining Shotcrete Drain Mat

In Region 3, where beamline equipment was installed, steel drip ceilings were placed above sensitive equipment, providing protection against groundwater and condensate drips. In Region 4, where the most moisture sensitive equipment was installed, environmental conditions were further enhanced through the introduction of low-humidity air (RH<10%).

The NuMI underground facilities have now been in operation for over five years. During this period a millimetric-level of foundation stability has been maintained for all beamline components and water inflow rates of between 500 and 1000l/min have been accommodated. No negative impacts on other Fermilab operations or the regional groundwater table have been reported during this period.

## USE OF SHOTCRETE ON FUTURE UNDERGROUND PHYSICS PROJECTS

Recent experience at NuMI demonstrates that shotcrete can serve successfully as a final lining for physics laboratories in an aquifer setting. Used in conjunction with appropriate rock reinforcement, water control and air conditioning measures, shotcrete can deliver fit-for-purpose rock openings that meet strict laboratory demands for operational stability and dryness.

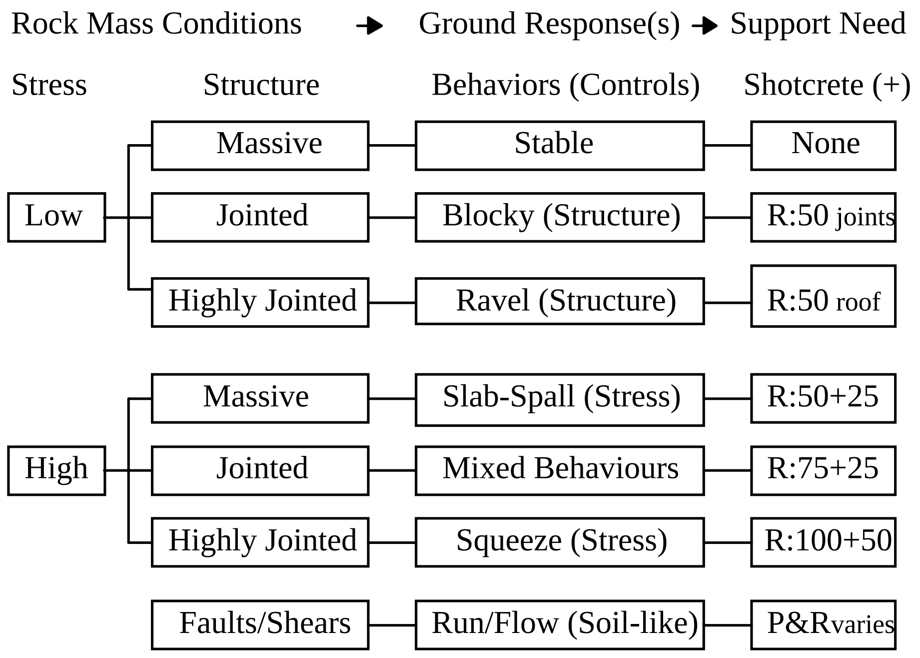
Shotcrete is now being proposed as a permanent liner for a major new underground facility, the Deep Underground Science and Engineering Laboratory (DUSEL). This laboratory is to be sited within the footprint of the old Homestake Gold Mine, Lead South Dakota, United States of America (P5 Panel, 2008 3).

Currently, work at the mine is focused on reopening two shafts to regain access to old workings sited at a depth of some 1500m. Once access is reestablished to this depth, a phase of rehabilitation and upgrade work will be performed to support the development a fledgling research campus. Follow-on rehabilitation phases will accommodate the development of a shallow campus (~100m deep), and the refurbishment of the network of tunnels, ramps and winzes necessary to access the deepest reaches of the mine, some 2400m below surface.

A major construction effort will be necessary in order to upgrade the early-20th century mine workings, construct new openings and install the infrastructure networks capable of supporting the safe and efficient operation of a 21st century National Laboratory. Shotcrete will be a key construction material used in the lining of the re-habilitated and new openings. As noted above shotcrete can contribute to long-term excavation stability, and facilitate the maintenance of the controlled environment necessary to support core laboratory functions.

Based on past experience at the mine, ground support systems will need to be designed to mitigate against a range of ground behaviors, primarily driven by the actions of gravity (block and wedge fall-outs), and/or in situ stress (squeeze and burst activity). The mine is sited in heavily-folded, meta-sedimentary rock units and pronounced foliation and jointing are observed in the intact material and rock mass respectively. Faults, fracture zones, and intrusive structures (dykes) are present across the site. Squeeze and burst phenomena were reported at depth.

A chart providing initial guidance on the use of shotcrete under a range of rock mass conditions is shown in Figure 6. This figure is based on Hoek's recommendations (4) relative to the use of shotcrete in combination with rock reinforcements (bolts and cables) in metamorphic rock units.



Shotcrete Thickness in mm (P - Plain; R - Reinforced)

Figure 6: Shotcrete to Mitigate Adverse Behaviors at DUSEL

In low in situ stress environments, present at the upper levels of DUSEL, shotcrete can be used to supplement rock reinforcement as a single pass application. Here, shotcrete will serve primarily to seal fractures bounding block and wedge traces. In more highly jointed masses it can also be applied more rapidly and extensively to arrest or prevent the on-set of ravelling. In massive rocks under low stress the chart indicates that no shotcrete is required. However, where there is a requirement for long-term personnel access or occupancy, a minimal thickness of shotcrete (P-25) may be warranted to minimize the need for maintenance work.

Under high stress conditions, a two pass application is generally recommended. A first layer is placed upon excavation, bolt and/or cable reinforcement installed, and a second shotcrete layer then sprayed (e.g. R50+25). Under mild rock burst conditions, Hoek suggests that a one-pass lining could be applied after bolts and surface lacing/mesh are installed.

In fault and fracture zones, Hoek suggests removing a depth of the soil-like or fractured fill materials and replacing them with plain shotcrete. An inner sleeve of reinforced shotcrete can then be installed and anchored to unaltered rock bordering the weak zone.

As can be surmised from the above discussions, shotcrete can provide a “first response” to address a range of DUSEL rock conditions. Used in combination with water control and air conditioning measures, shotcrete can provide the science and engineering community with a stable, long-lived, dry environment within which they can perform a new generation of research experiments.

## CONCLUSIONS

Shotcrete is increasingly being used to fulfill permanent lining roles on underground physics projects. It provides design and construction contractors and the owner with enhanced opportunities to tailor the facility to research requirements while offering greater potential to reduce costs and the time to research.

For many underground laboratories, shotcrete is an acceptable alternative lining. Used in combination with water control and air conditioning systems, shotcrete can meet the strict stability and dryness demands of the researcher, even for facilities sited below the water table in wet conditions.

Shotcrete is likely to find widespread use at the DUSEL. Applied in combination with rock reinforcements it can effectively mitigate against the range of geo-structural and stress-controlled failure modes likely to be encountered across the site.

## REFERENCES

1 Laughton, C. “”Rock Support of the Experimental L3 Hall Complex.” Proceedings of the International Symposium on Unique Underground Structures Denver, Colorado, USA. June 1990. Vol. 1, Paper 49, pages 9.
2 Lamour, A. “Redpath completes $65 million SNOLAB Expansion.” Sudbury Mining Solutions, September 2008, pages 16-17.
3 P5 - Particle Physics Project Prioritization Panel Report “US Particle Physics: Scientific Opportunities A Strategic Plan for the Next Ten Years.” 29th of May 2008, pages 100.
4 Hoek, E. “Shotcrete Support.” http://www.rocscience.com/hoek/pdf/16 Shotcrete_ support.pdf