Introduction

While organizing this conference, the disappointing discovery was made that very few important shotcrete projects had been performed in North America in the last three years. However, as evidenced by the papers given at the conference, considerable work of great interest has been performed in many other parts of the world. In Europe the use of the New Austrian Tunneling Method (NATM) seems to be spreading rapidly, even to countries that pride themselves on their individuality.

In North America, large projects utilizing shotcrete are frequently built by general contractors, without recourse to the specialized sub-contractor. A great disappointment of this conference has been low attendance of American general contractors, despite the proximity of large shotcrete projects in nearby Washington.

This conference has dealt with shotcrete for ground support, and the subject matter therefore entails considerable overlap with other support or rock reinforcement elements such as steel ribs and rockbolts, and with different excavation procedures. While the first part of the program concerned shotcrete alone, the second described the driving of tunnels, cavities, and shafts under difficult conditions, with the use of shotcrete supplying the major link between papers.

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The present state-of-the-art, as described at this conference, is briefly summarized below, under the major topic titles.

Materials and Field Control

Fiber-reinforced shotcrete has become a viable alternative to the use of wire mesh with shotcrete. This application provides increased ductility and flexural strength to shotcrete coatings, without the disadvantages of using wire mesh. These disadvantages include the occurrence of laminations and sand pockets caused by difficult placement around the wire, excessive thicknesses to cover mesh not conforming to rock surfaces, and increased labor requirements. Fiber-reinforced coatings may find use not only in rehabilitation of old structures and slope stabilization, but also as final linings where public safety is involved.

The use of accelerated-set admixtures for shotcrete has progressed, with greater availability of liquid products and suitable metering devices. Of particular interest is the introduction of an organic accelerator, which if expectations are fulfilled, will not only improve the product but also jobsite environmental conditions. Less encouraging are the limited reports on use of fast-setting or regulated-set cements, which eliminate the need for accelerators.

A large range of reported shotcrete compressive strengths illustrates the variability of this product, as well as inconsistencies in reporting procedures. Although it is generally recognized that accelerators adversely affect shotcrete strength, reported strengths often refer to unaccelerated vertically oriented test panels, a convenient form of testing. Results of in situ sampling of overhead shotcrete frequently reflect lower strengths because of use of accelerators.
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(or higher accelerator dosages) and defective workmanship due to nozzleman discomfort from rebound.

Field control of shotcrete is complicated by important differences in sampling and testing procedures. Results quoted are meaningful only if specimen dimensions, shape, age, curing conditions, and accelerator content, as well as the application of correction factors to test data are described. Standardization of sampling and testing procedures is needed to eliminate existing discrepancies and confusion. Although all three values are frequently quoted, correlation between shotcrete cubes and cores, and concrete standard cylinders has not been defined. Useful work in this field is underway, however. Many designers consider that compressive strength is merely a useful indication of quality of workmanship but does not appreciably affect their "design".

Another facet of shotcrete quality, the percentage material rebounded, also is frequently misinterpreted. Recent studies have clarified the causes and properties of rebound, and standard test procedures for measuring rebound have been developed.

Equipment and Processes

There has been an impressive advancement in equipment design over the past few years. However, despite the marketing of several remote-controlled nozzle booms, and their obvious advantages over hand-held nozzles, these have not been used in large civil construction projects on this continent. Highly-automated equipment such as described at this conference for shotcrete placement in tunnels, caverns and shafts should increase the viability and economy of shotcrete linings.

Equipment for volumetric batching of shotcrete materials immediately prior to placement is becoming more prevalent due to avail-
ability of improved equipment. Such batching not only improves shotcrete setting and strength characteristics but also eliminates contractor reliance on sometimes unresponsive or inconveniently located ready-mix suppliers.

The wet-mix versus dry-mix debate continues due to advantages and disadvantages of both systems. Improvements in dry-mix equipment, particularly nozzles, have reduced some of the advantages of the wet-mix process. Moreover, disadvantages of the wet-mix process have become more apparent with increased use of accelerated set wet shotcrete. With development, the disadvantages of both systems will probably be minimized and their use continued for differing applications.

Little progress has been reported on combination of shotcrete placement with excavation by full face tunnel boring machines. Cutter boom mining machines however, are reported to be compatible with shotcrete application.

Payment Provisions

Payment provisions for shotcrete linings are becoming more frequently written as lump sum payments (so much per square yard or linear foot of tunnel) rather than by measured or calculated volume. This practice encourages good workmanship and protects the owner from quantity overruns and subsequent claims. Contractors favor payment for volume through the machine to reduce their risk of compound costs due to unforeseen conditions. Perhaps proper application of changed condition clauses and increased experience by designers, contract administrators and contractors in the use of shotcrete will lead to acceptance of the lump sum method, as has occurred in much of Europe. The heat of the current
argument underlines the need for improved contracting practises in North America.

Design

The present state-of-the-art of design of underground structures utilizing shotcrete may be defined as theoretical, empirical, or theoretical-empirical methods. A theoretical method described was the current Washington Metro station design, which considers shotcrete and embedded steel rib supports as a composite structure resisting hypothetical gravity loads imposed by rock blocks. Empirical methods, or rules of thumb are frequently used for design of shotcrete initial support or final linings in tunnels. Several such procedures were proposed at the last shotcrete conference. A combination of methods called the New Austrian Tunneling Method (NATM) has been developed and utilized extensively in Europe. This method considers the reinforced and protected ground surrounding an opening to be the supporting element, rather than the lining itself. A relatively thin reinforced shotcrete lining provides a major protecting and minor supporting function, containing the rock and inhibiting strength loss due to detrimental loosening. Fully bonded rockbolts contribute the major rock reinforcing element, particularly for openings with large cross-section.

The theoretical analysis for the NATM describes the formation of a plastic zone around the opening which ultimately fails in longitudinal shear if not properly reinforced and confined. Such an analysis is quite applicable to highly stressed metamorphic rocks at great depths in the Alps, and to cohesive soft ground at moderate depths, as evidenced by observation. Empirical backup for design is provided by experience
in numerous projects, which have been extensively monitored by standardized instrumentation. Ground and lining behavior is monitored during construction and compared with previous experience, permitting timely changes in supporting elements, construction method or sequence. Although the NATM has been successfully used in most kinds of ground, it must be assumed that designs in blocky low cover rock, such as encountered in Washington, owe little to the theoretical analysis described above.

Two and three dimensional model tests of the effects of rock block movement on shotcrete linings have provided useful empirical input to the theoretical "composite structure" design method, as has extensive in situ rock and lining measurement. However, present methods do not take into consideration the rock reinforcing effect of rockbolts, which normally supply most or all of the "support" for large underground openings in mines and powerhouses.

It is apparent that different design procedures are required for different ground conditions, cavity dimensions, and uses. A method which permits flexibility for changing design during construction as a result of feedback from observation and instrument monitoring probably provides the most practical solution to the always unpredictable underground condition. In order to permit increased flexibility during construction, contracting practices will have to be altered.

Case Histories

The use of shotcrete for ground support was illustrated by a number of case histories from the United States, Great Britain, Austria, Spain, Germany, Costa Rica, Japan, France, and Colombia. Its function in providing support or ground reinforcement alone, or in combination with other elements is impressive. Of particular interest
are the various means of combining these elements to permit tunneling through overstressed schists and phyllites, sandy and marly sediments, blocky foliated gneiss, meta-sediments, volcanic tuffs, and overstressed shale and claystones. Shotcrete is seen to have become internationally a very important tool for tunneling under the most extreme conditions. Its use for rock support in large scale shaft sinking operations was also of interest.

Several complex underground structures for subways in Germany provided background for an analysis of costs and practical advantages of the NATM. Despite the labor-intensive nature of this construction method, economies were realized compared with conventional open-cut designs or short shield driven tunnels. The importance of knowledgeable engineers and contractors for successful application of the method was emphasized.

Performance

The performance of shotcrete-lined tunnels may be described as either short-term or long-term. Short-term performance is generally monitored during construction with instrumentation and observation to permit alteration of construction method, sequence or even design. Long-term performance involves service experience with shotcrete final linings, to permit careful evaluation of their proper usage.

Monitoring of lining and ground loads and displacements plays an important part in construction of many major underground civil works, including powerhouses, subway stations, and work employing the NATM. Given the difficulties involved in obtaining accurate and meaningful measurements, part of the success of the NATM is perhaps attributable to a standardization of measurement techniques, utilizing fairly simple and
reliable instruments.

Although many shotcrete lined tunnels, particularly in Scandinavia, have successful service records of up to twenty years, very little information on the long-term durability of shotcrete linings is available. A number of unfavorable experiences with tunnels lined with shotcrete point out some of the pitfalls which must be avoided. These tunnels were completed without incident but failed after a few years service, due to swelling of clayey fault gouges or fracture fillings, in the presence of water. Service conditions in tunnels, and their impact upon ground and lining durability must be carefully evaluated by designers.

In concluding, some modest goals should be proposed, applying particularly to the United States and Canada.

1. Shotcrete specifications and testing procedures should be rationalized.
2. Greater utilization of available equipment and products should be made to improve shotcrete quality and jobsite environmental conditions.
3. Pre-construction design methods should be improved and greater flexibility encouraged to permit design changes during construction.
4. The NATM should be introduced to North America in such a way as to ensure its success, so that all may benefit from its advantages.